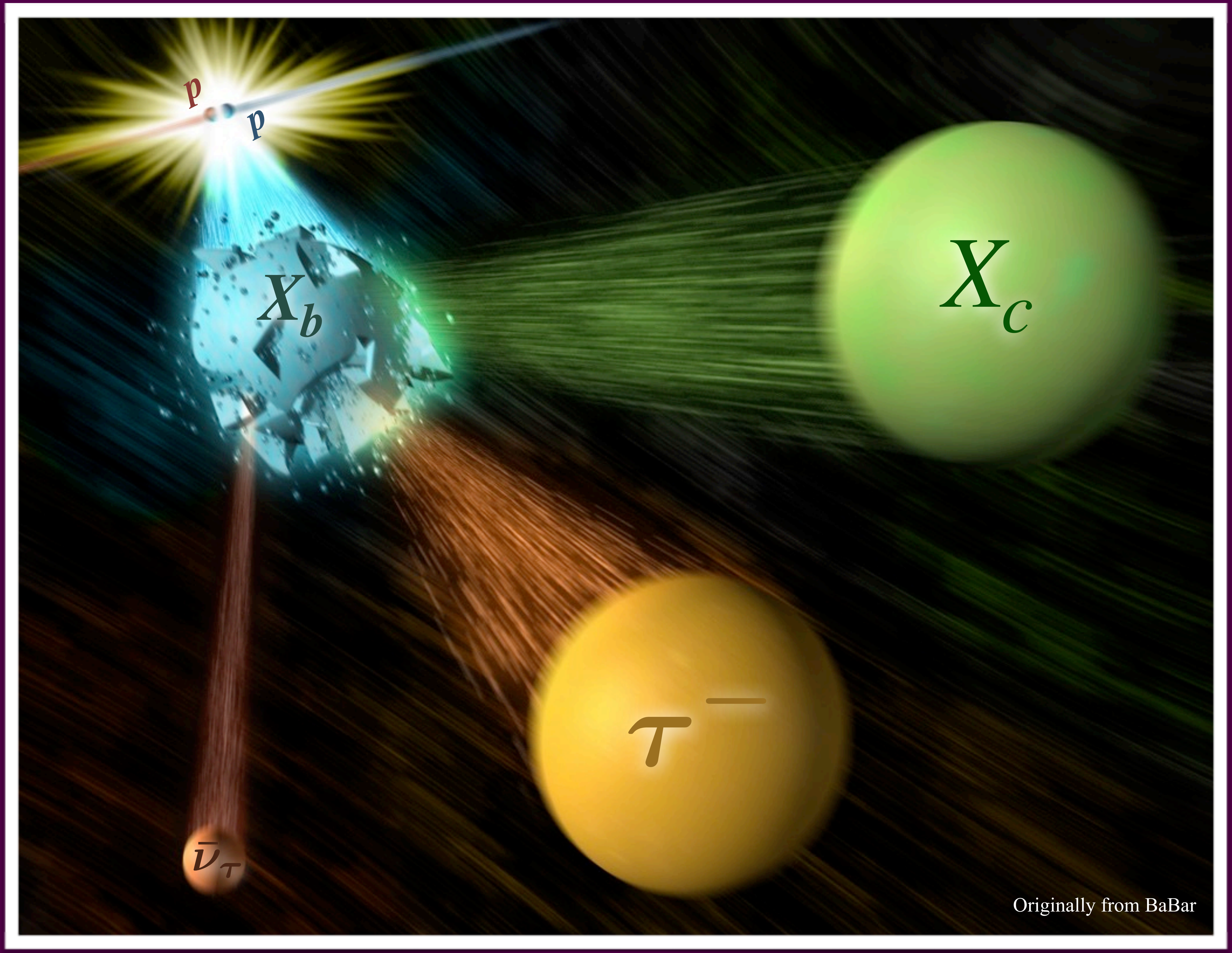
LUV in charged-current b decays at LHCb



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<u>**29th September 2020**</u>

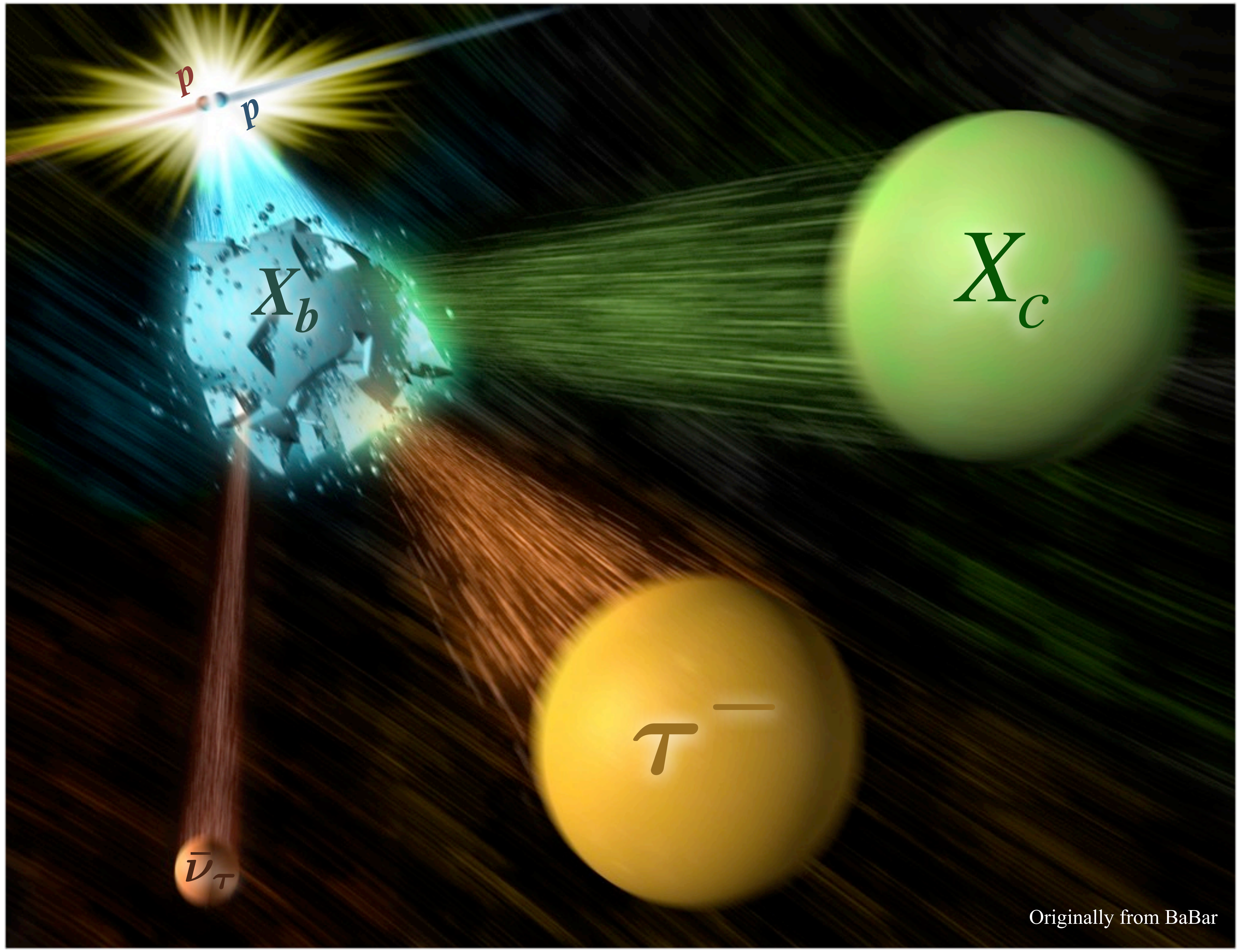
Snowmass 2021

RF1: Weak decays of b and c quarks

RF5: Charged Lepton Flavor Violation (electrons, muons and taus)

Outline

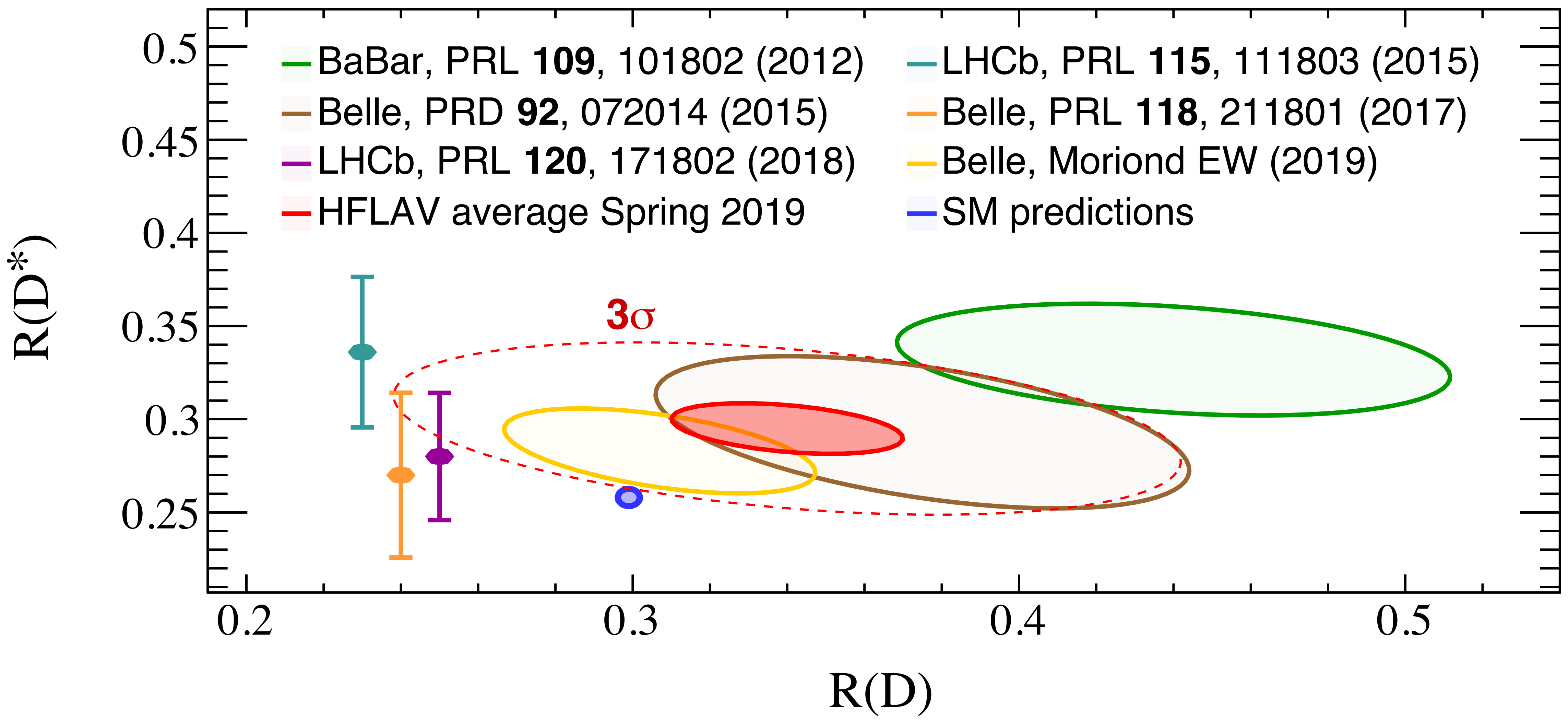
LHCb has **access** to **several** interesting **decays** with a **tree-level $b \to c\tau\nu$ transition**



- **Brief introduction**
  - Current charged LUV measurements
  - LHCb detector
  - Vertex isolation
- **Features** of LHCb measurements
  - Muonic τ decay analyses
  - Hadronic τ decay analyses
- **Prospects** for charged LUV at LHCb
  - Possible precision on $\mathscr{R}(X_c)$
  - Measuring kinematic distributions

Charge-current LUV status

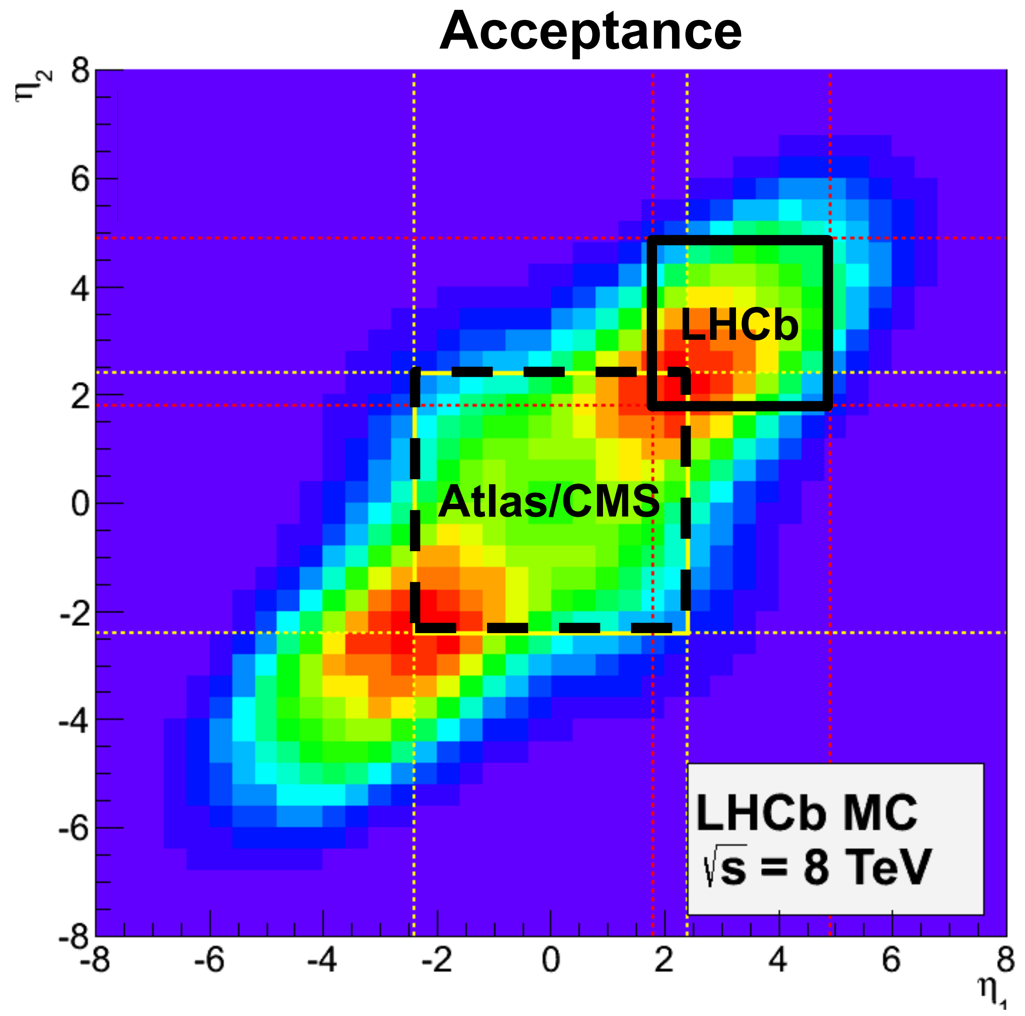
Experiment	τ decay	Tag	$\mathcal{R}(D)$	$\sigma_{\rm stat}$ [%]	$\sigma_{\rm syst}$ [%]	$\mathcal{R}(D^*)$	$\sigma_{\rm stat}$ [%]	$\sigma_{\rm syst}$ [%]	$\rho_{\rm stat}/\rho_{\rm syst}/\rho_{\rm tot}$
BABAR[a]	$\mu\nu\nu$	Had.	$0.440 \pm 0.058 \pm 0.042$	13.1	9.6	$0.332 \pm 0.024 \pm 0.018$	7.1	5.6	$-0.45/-0.07/-0.31$
Belle[b]	$\mu\nu\nu$	Semil.	$0.307 \pm 0.037 \pm 0.016$	12.1	5.2	$0.283 \pm 0.018 \pm 0.014$	6.4	4.9	$-0.53/-0.51/-0.51$
Belle[c]	$\mu\nu\nu$	Had.	$0.375 \pm 0.064 \pm 0.026$	17.1	7.1	$0.293 \pm 0.038 \pm 0.015$	13.0	5.2	$-0.56/-0.11/-0.50$
Belle[d]	$\pi\nu$	Had.	–	–	–	$0.270 \pm 0.035^{+0.028}_{-0.025}$	13.0	$^{+10.3}_{-9.3}$	–
LHCb[e]	$\pi\pi\pi\nu$	–	–	–	–	$0.280 \pm 0.018 \pm 0.029$	6.4	10.4	–
LHCb[f]	$\mu\nu\nu$	–	–	–	–	$0.336 \pm 0.027 \pm 0.030$	8.0	8.9	–
Average[g]	–	–	$\mathbf{0.340 \pm 0.027 \pm 0.013}$	**7.9**	**3.8**	$\mathbf{0.295 \pm 0.011 \pm 0.008}$	**3.7**	**2.7**	$\mathbf{-0.39/-0.34/-0.38}$

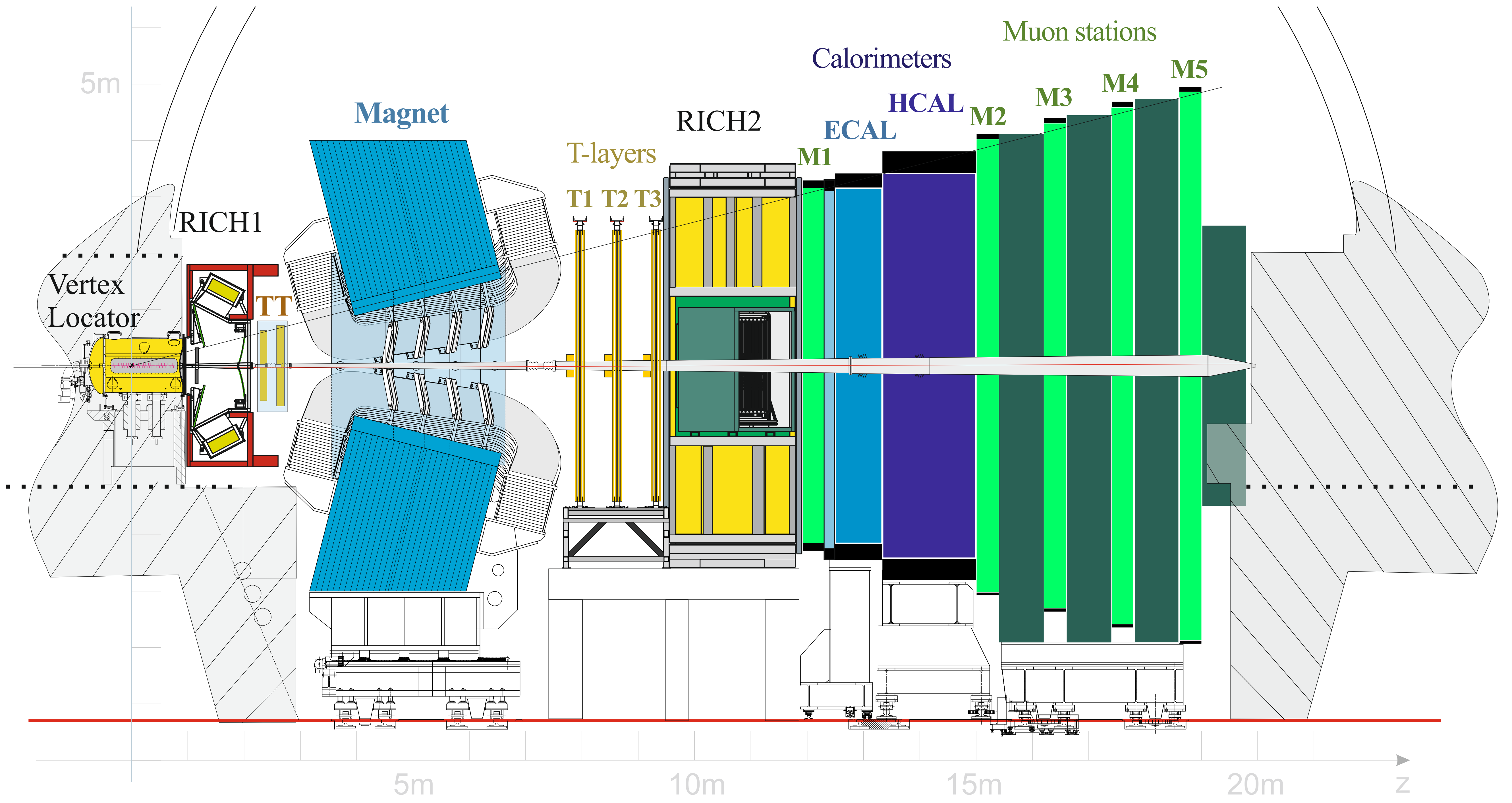


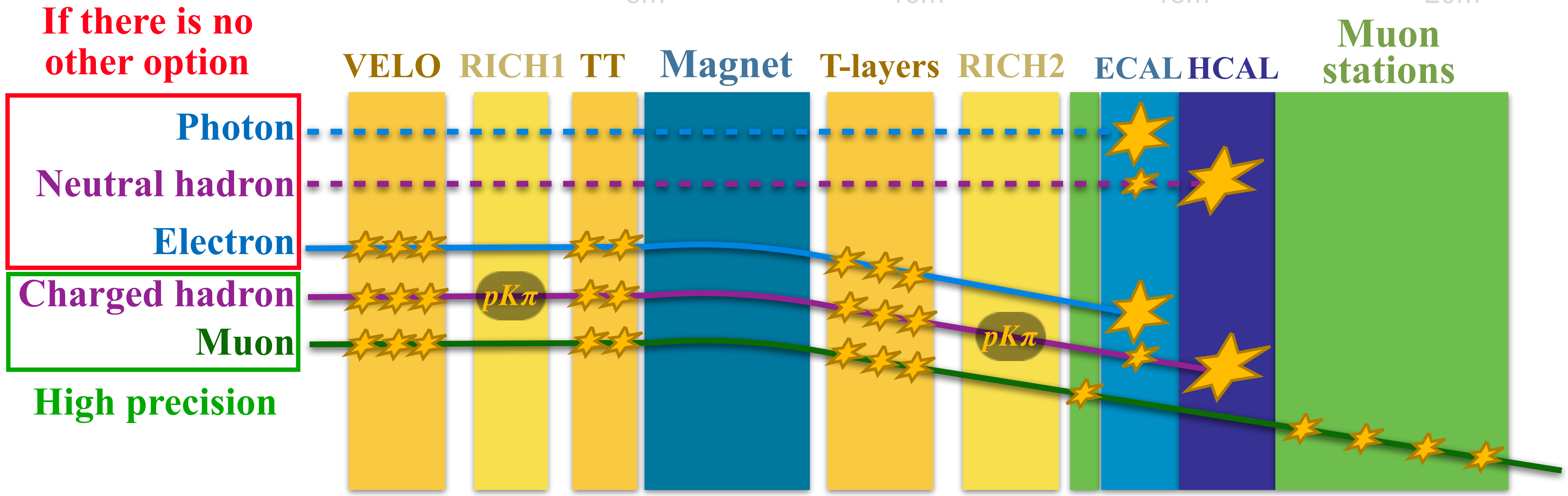
- **Significant deviation** in $\mathscr{R}(D^{(*)})$ from SM
  - Measurements from BaBar, Belle, and LHCb
- Additionally, LHCb measures $\mathscr{R}(J/\Psi) = 0.71 \pm 0.17 \pm 0.18$
- Any anomaly will need to be characterized with **independent rate** and **distribution measurements**
- Is **LHCb systematics limited** already?
  - **No!** Let's see how

The LHCb experiment

- GPD with focus on **flavor physics**
  - 25% of $b\bar{b}$ production with 4% of solid angle ($2 \le \eta \le 5$)
  - 100k b-hadrons produced every second







- Excellent **secondary vertex reconstruction**
- **PID**: π, K, p, μ

Upgrades

9 fb^{-1}			Upgrade I	Goal: 50 fb^{-1}			Upgrade II	Goal: 250 fb^{-1}		
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024	2025 2026 2027	2028 2029 2030	2031	2032 2033 2034	2035	2036 2037

Runs 1 and 2

40 MHz pp collisions → **L0** Hardware → 1.1 MHz Detector readout → **HLT** Software → 12.5 kHz (0.6 GB/s) Events on disk

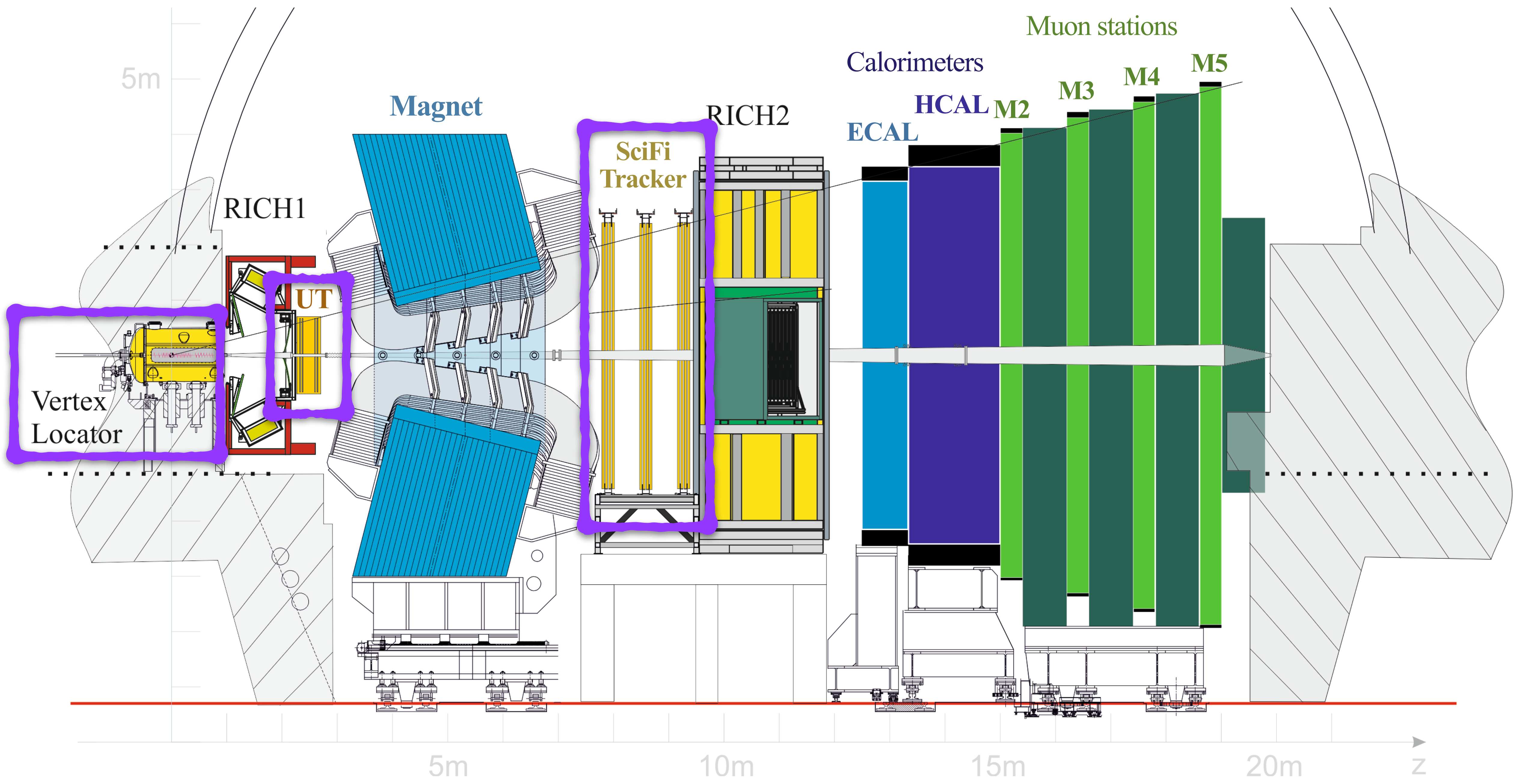
Upgrade I (being installed)

40 MHz pp collisions Detector readout → **HLT** Software → 100 kHz (2-5 GB/s) Events on disk

Flexible software and better trackers

Upgrade II (proposed)

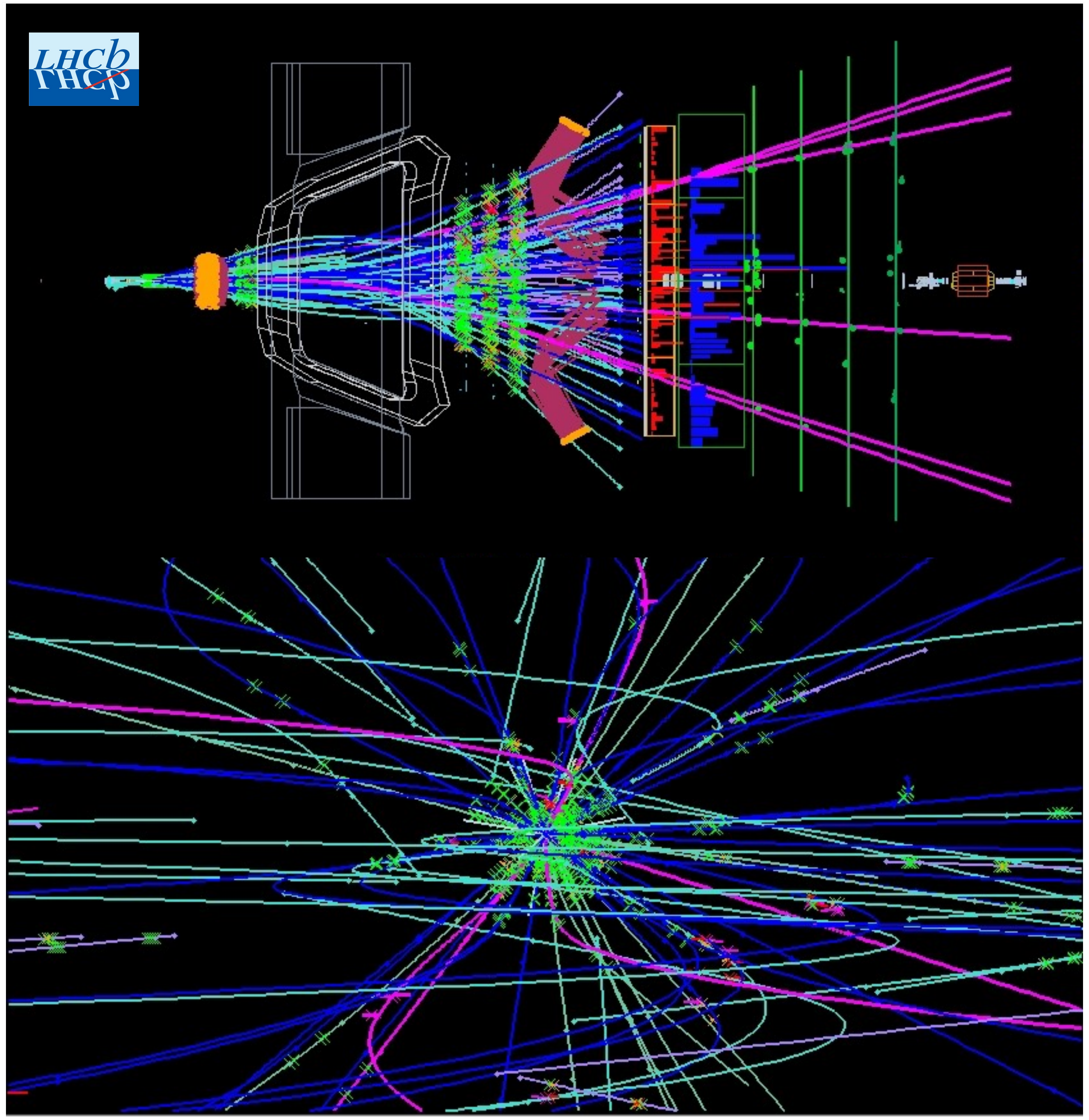
Even better granularity, improved calorimeter, and fast timing



Busy environment

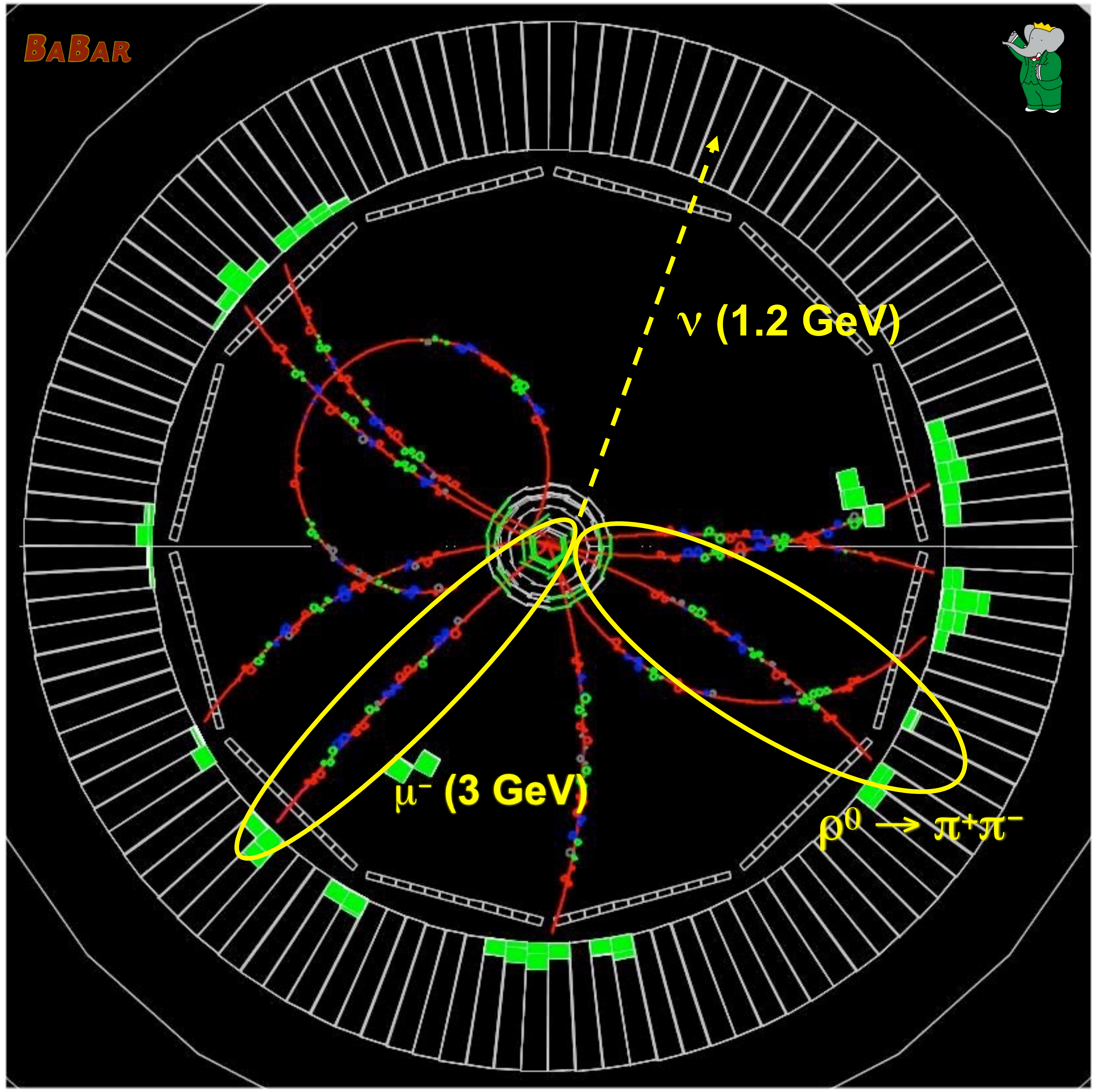
$pp \to X_b B_s^0 X$

$B_s^0 \to \mu^+\mu^-$



$e^+e^- \to B^+_{\text{tag}} B^-_{\text{sig}}$

$B^- \to \rho^0 \mu^- \nu_\mu$



B-factory advantages

Lower backgrounds

Collision momentum known

Neutrals and electron reco

LHCb advantages

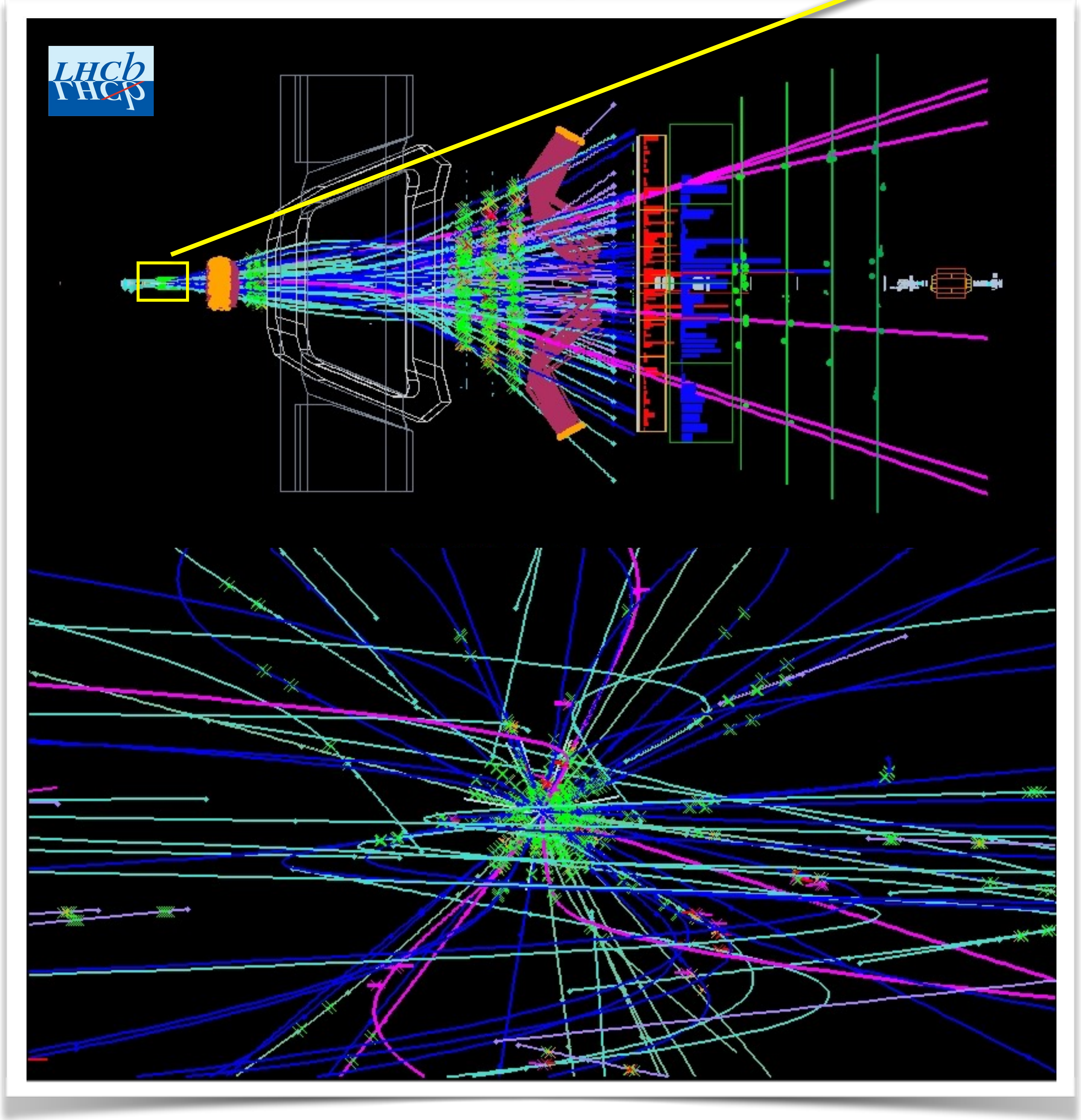
Higher statistics

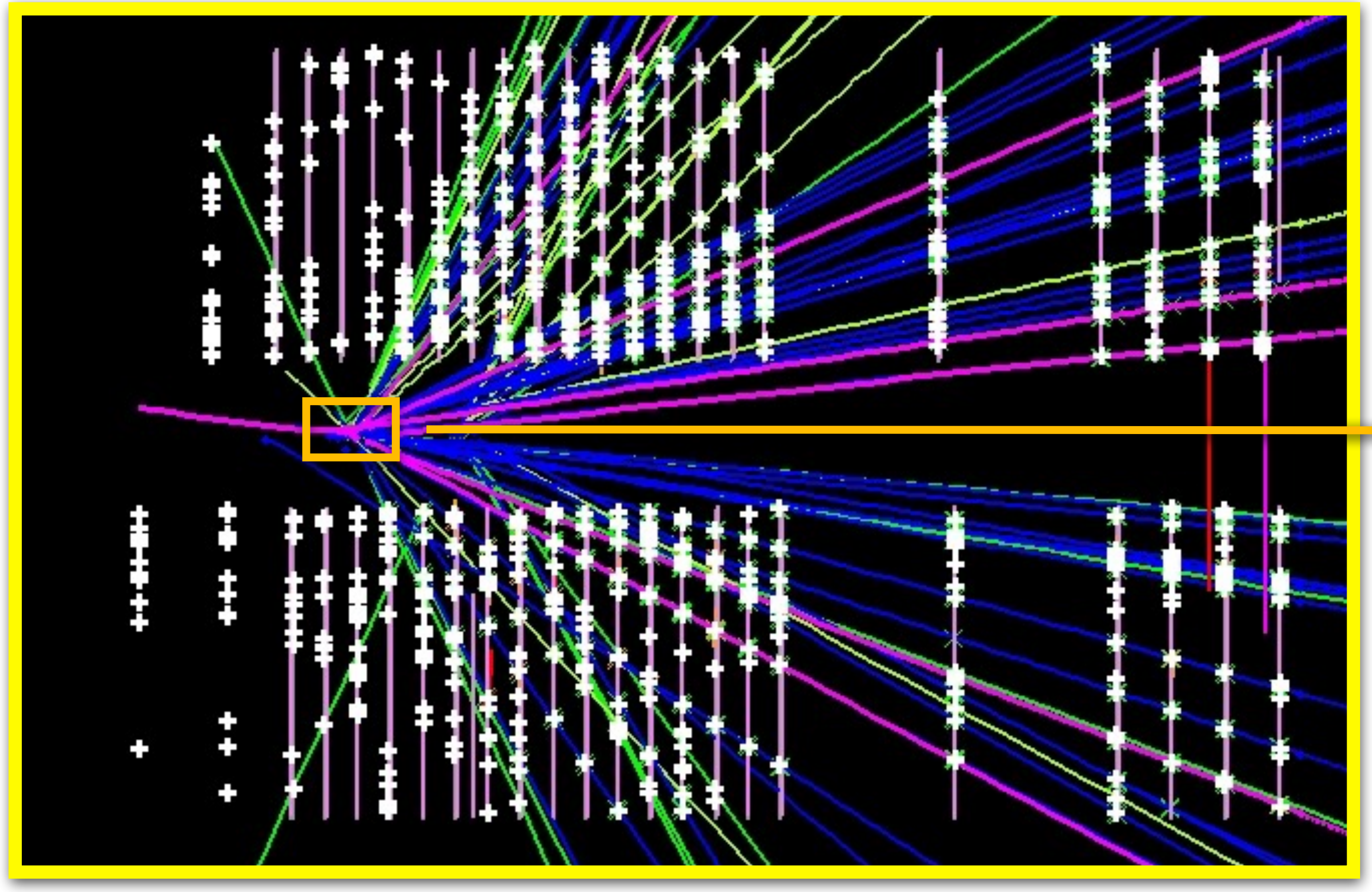
All b-hadron species

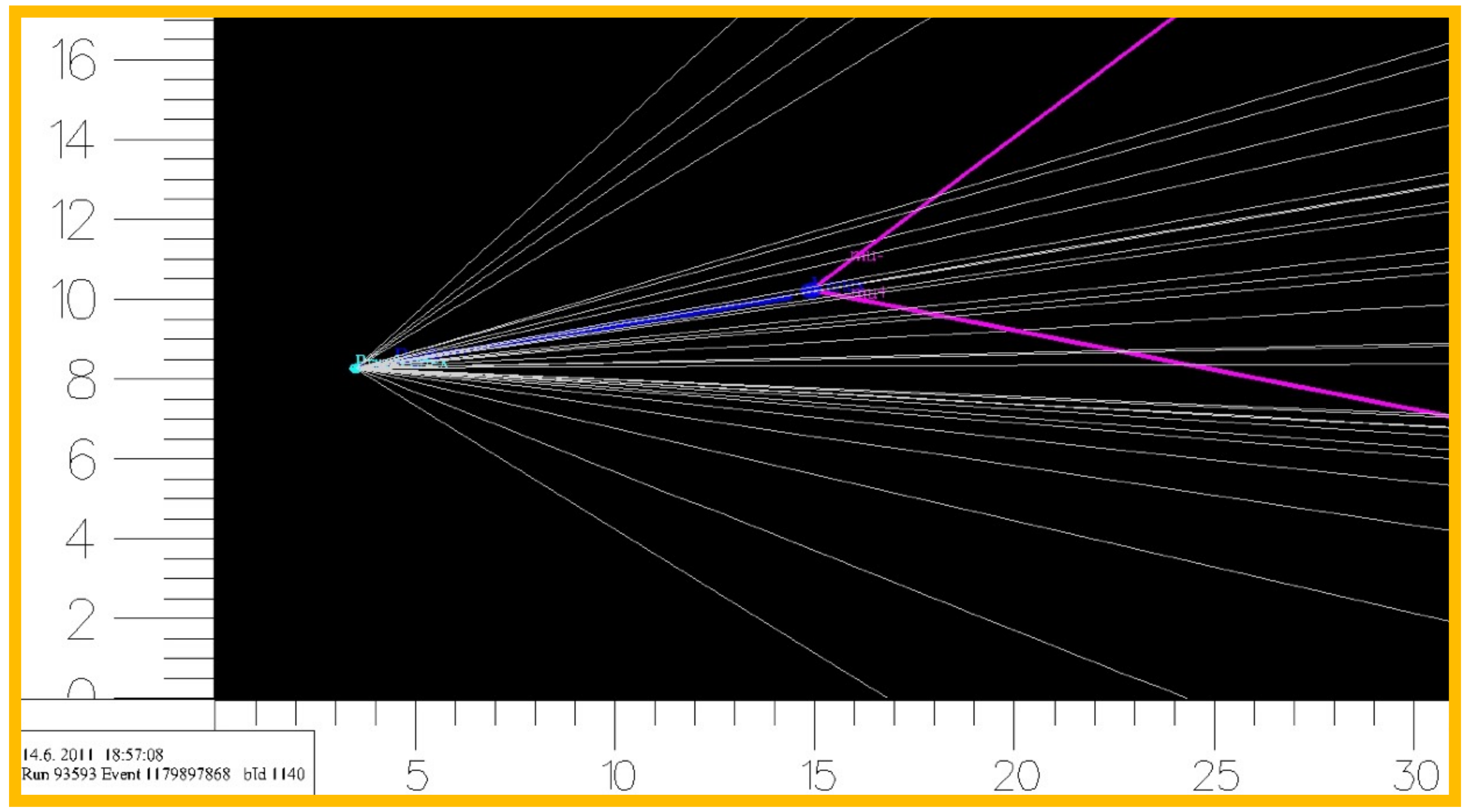
Larger boost

$$pp \to X_b B_s^0 X$$

$$B_s^0 \to \mu^+\mu^-$$

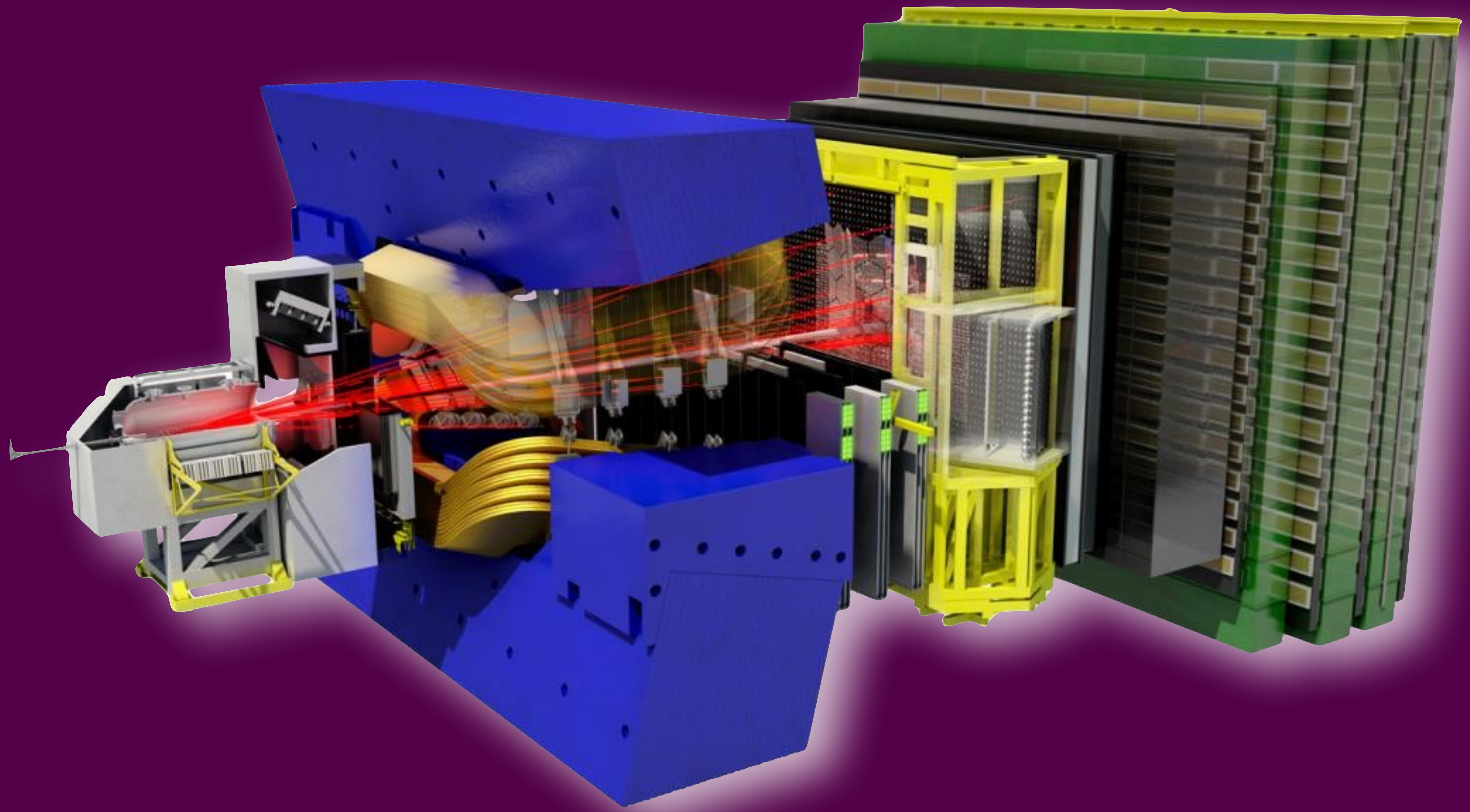






- Superb vertexing by VELO (in vacuum)
  - Only 8.2 mm from IP, 300 μm of material
  - Reduced to 5.1 mm from IP, 150 μm of material in upgrade
- **B mesons fly several cm** thanks to large boost
- Developed **isolation BDT for** $\mathscr{R}(D^*)$ measurement
  - Assign probability of track coming from B vertex
  - $IP\chi^2_{PV}$, $IP\chi^2_B$, p_T, track angle, refitted B vertex with track

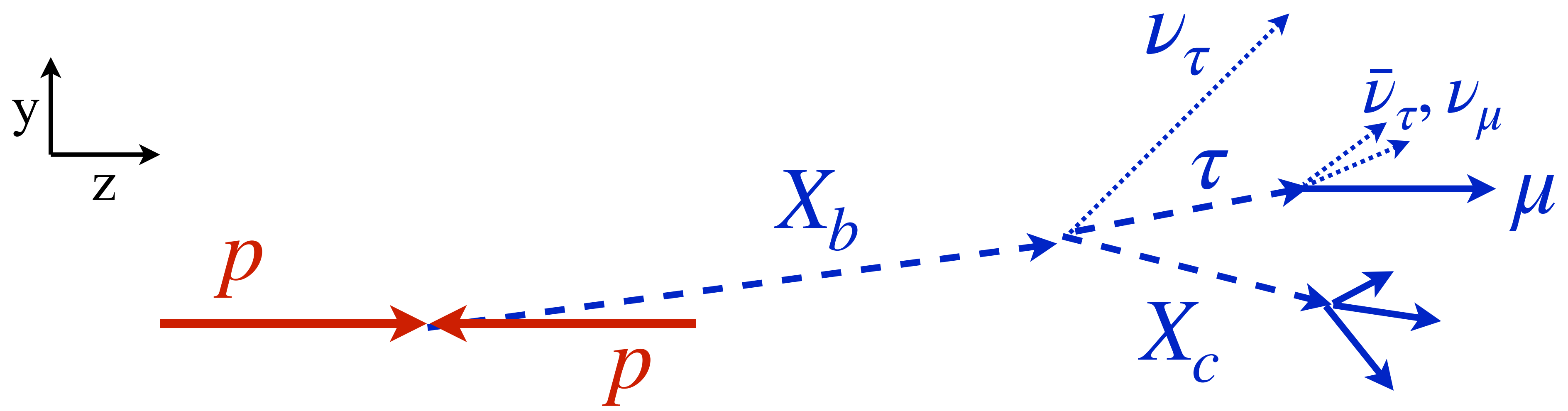
Features of LHCb measurements



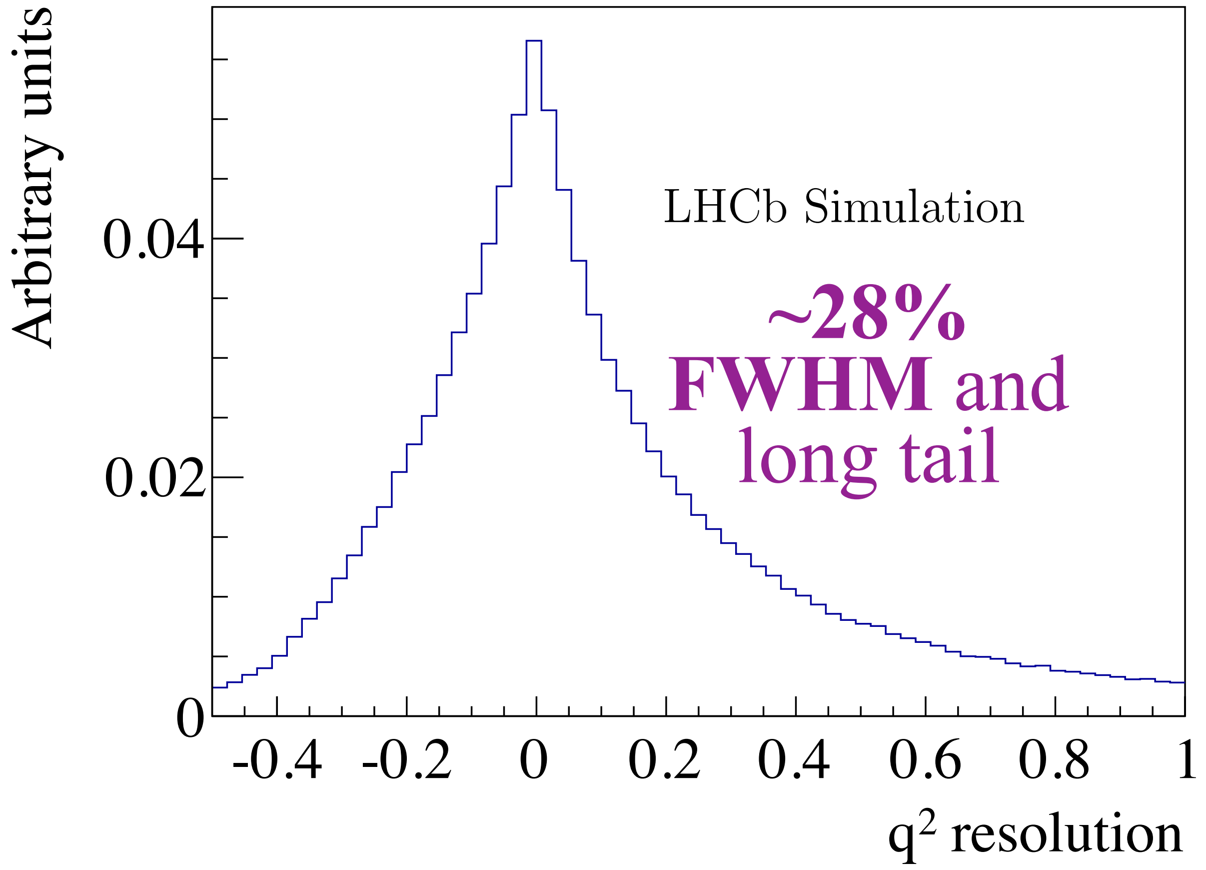
Rest Frame Approximation (RFA) for muonic τ

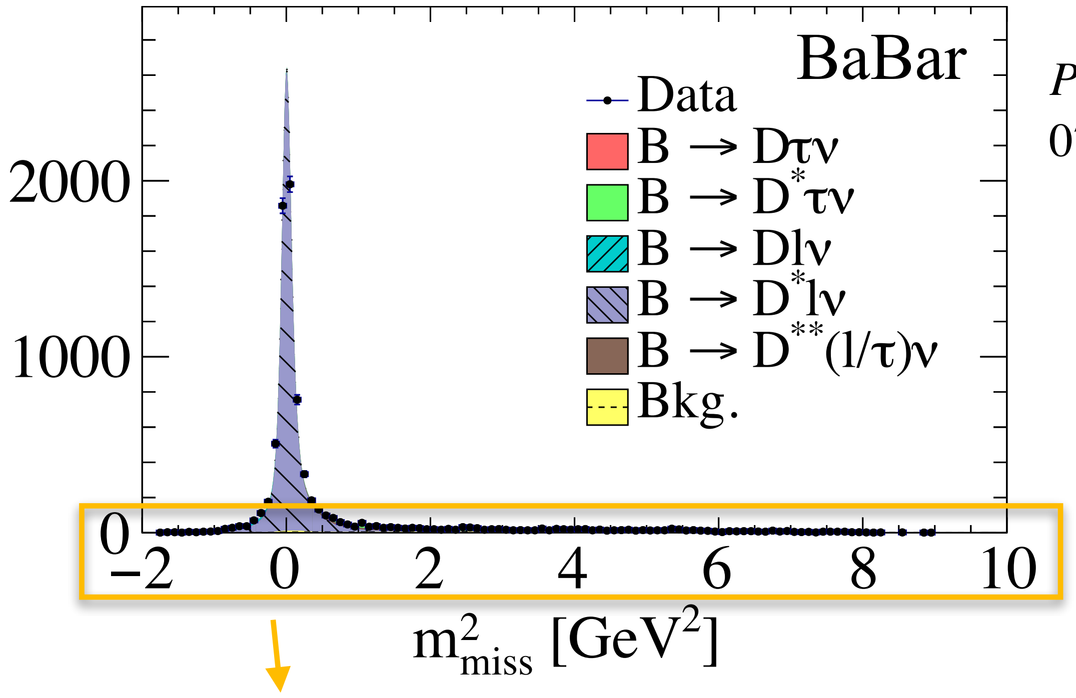
- **Same visible final state** for **signal/normalization** when $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ used
  - ➡ But $B \to D^{(*)}\tau\nu$ has 3 neutrinos, while $B \to D^{(*)}\ell\nu$ only 1
- B-factories effectively reconstruct $p_{B_{sig}}$ with B-tagging
  - ➡ $p_{B_{sig}} = p_{e^+e^-} - p_{B_{tag}}$ allows you calculate $p_{miss} = p_{B_{sig}} - p_{D^{(*)}} - p_\ell$
- LHCb estimates p_{X_b} with RFA
  - ➡ Good approximation thanks to large X_b boost

$$|p_{B_{sig}}| = \frac{m_B}{m_{\mu X_c}} \left(p_{\mu X_c}\right)_z \sqrt{1 + \tan^2\alpha}$$

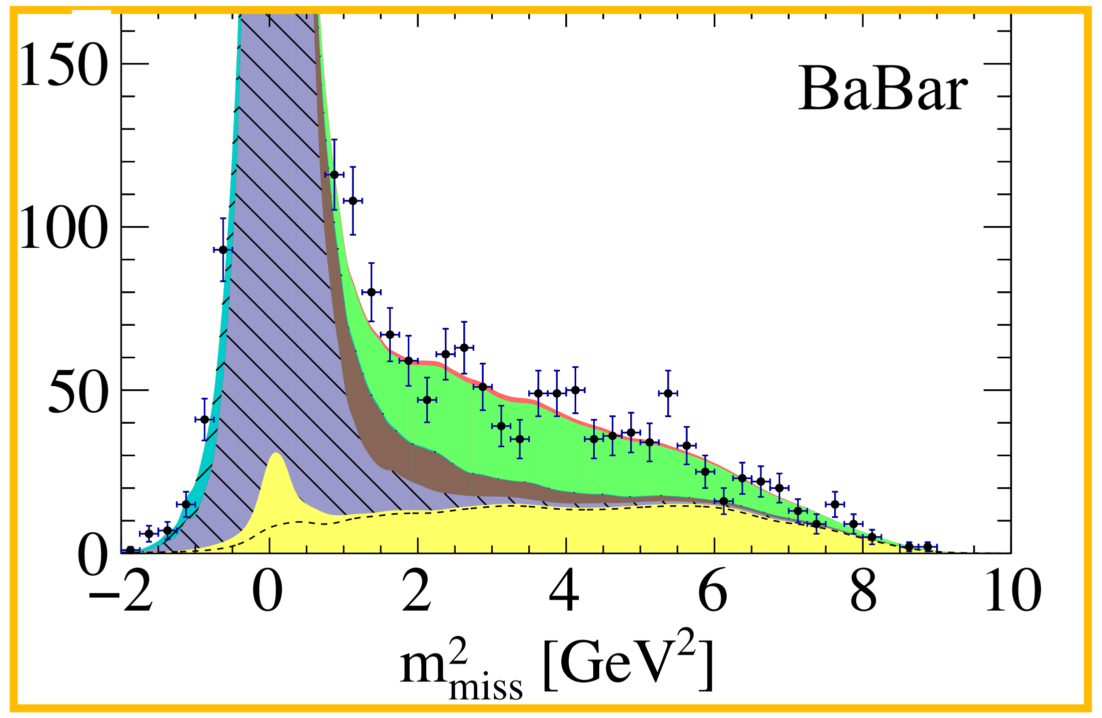


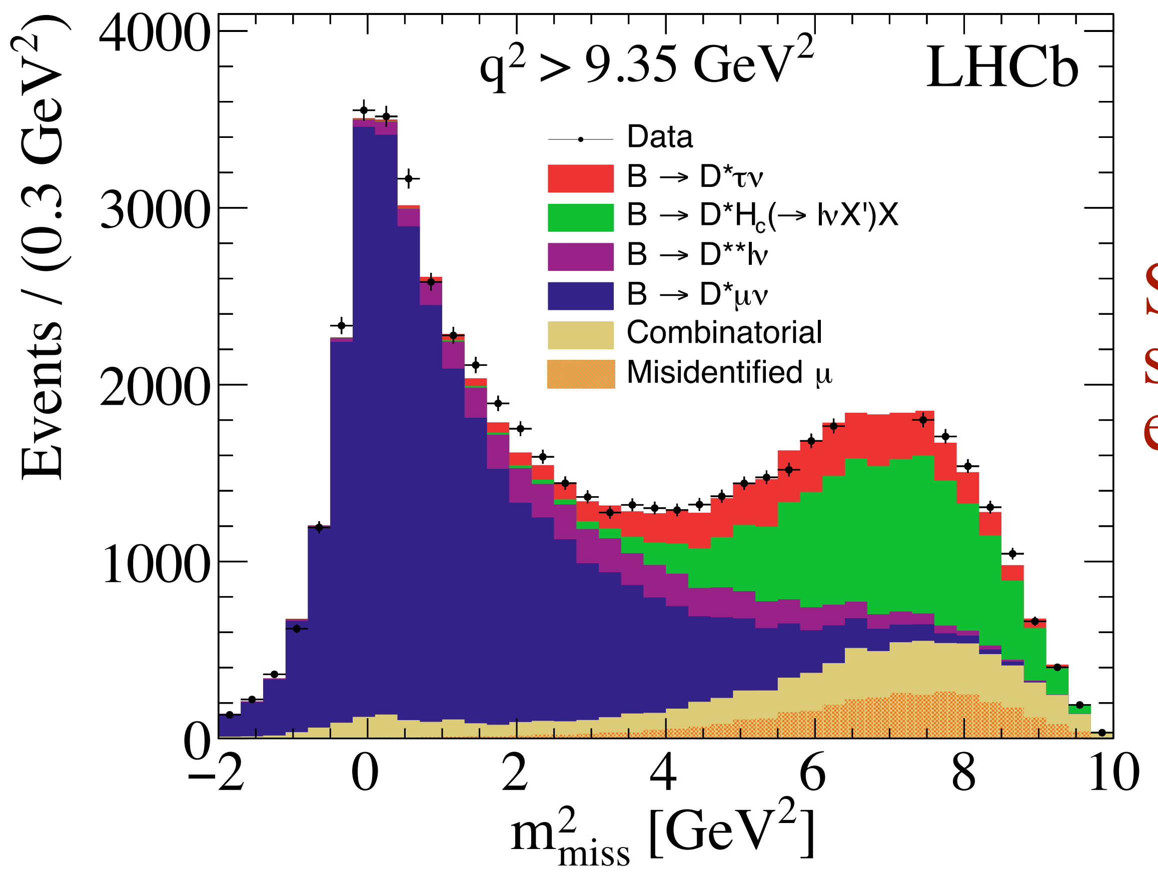
Phys. Rev. Lett. **115**, 111803 (2015)





Phys. Rev. D **88**, 072012 (2013)

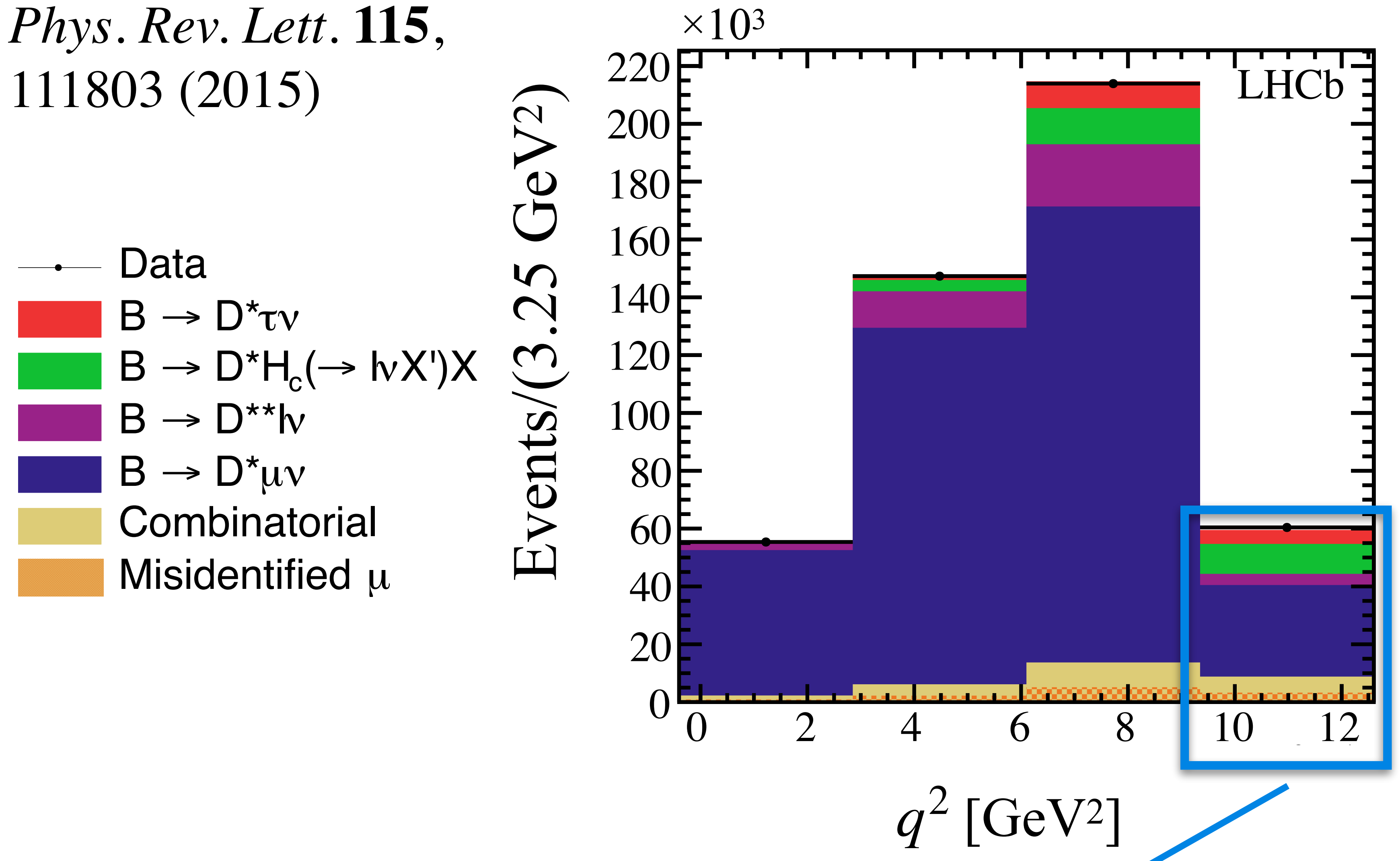




Sufficient separation if enough stats

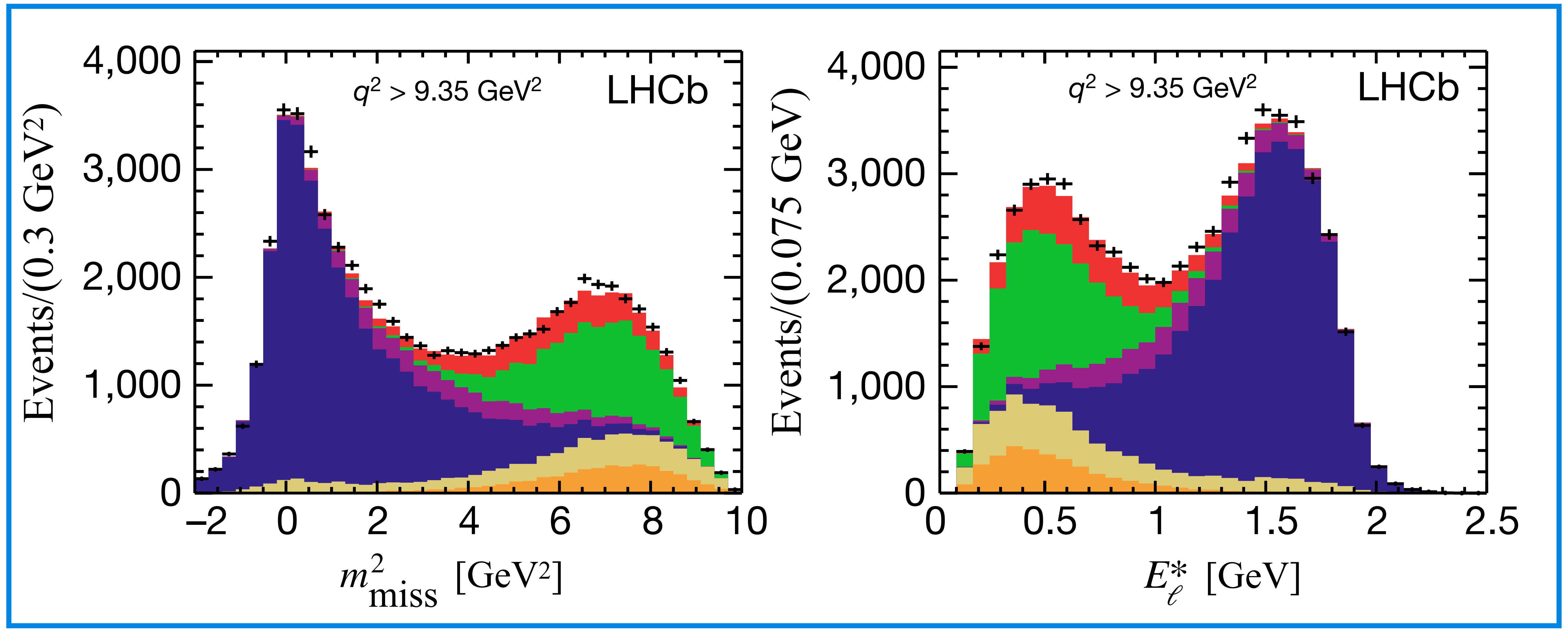
Muonic $\mathcal{R}(D^{*+})$

Phys. Rev. Lett. **115**, 111803 (2015)



- Proof of concept measurement in 2015
  - ➡ Not clear if possible beforehand!
- 3D simultaneous fit to q^2, m^2_{miss}, and E^*_μ

$$\mathcal{R}(D^*) = \frac{\mathcal{B}\left(\bar{B} \to D^*\tau\nu_\tau\right)}{\mathcal{B}\left(\bar{B} \to D^*\mu\nu_\mu\right)}$$



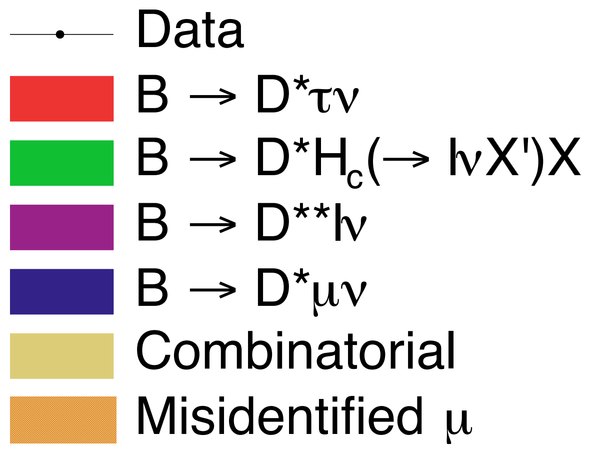
Decay mode used in *BABAR*			$\mathcal{B}(\%)$	
D^{*+}	$\to$	$\boxed{D^0\pi^+}$	67.7	LHCb
	$\to$	$D^+\pi^0$	30.7	
Total			**98.4**	
D^0	$\to$	$K^-\pi^+\pi^0$	13.9	
	$\to$	$K^-\pi^+\pi^-\pi^+$	8.1	
	$\to$	$K^0_S\pi^+\pi^-\pi^0$	5.4	
	$\to$	$\boxed{K^-\pi^+}$	3.9	LHCb
	$\to$	$K^0_S\pi^+\pi^-$	2.9	
	$\to$	$K^0_S\pi^0$	1.2	
	$\to$	K^+K^-	0.4	
Total			**35.8**	

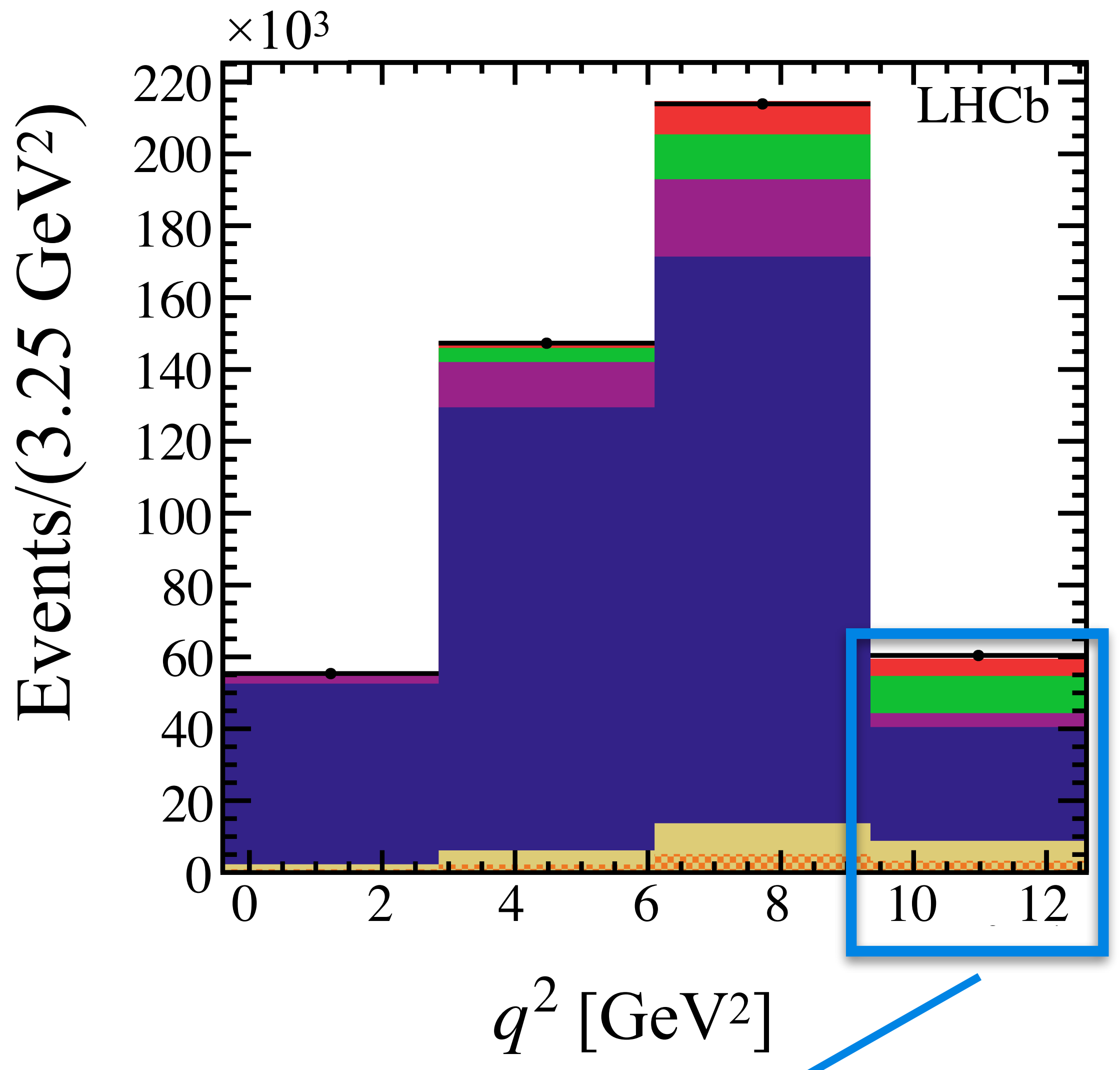
LHCb **only reconstructed** $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$

Could more than **double stats** adding **other fully charged final states**

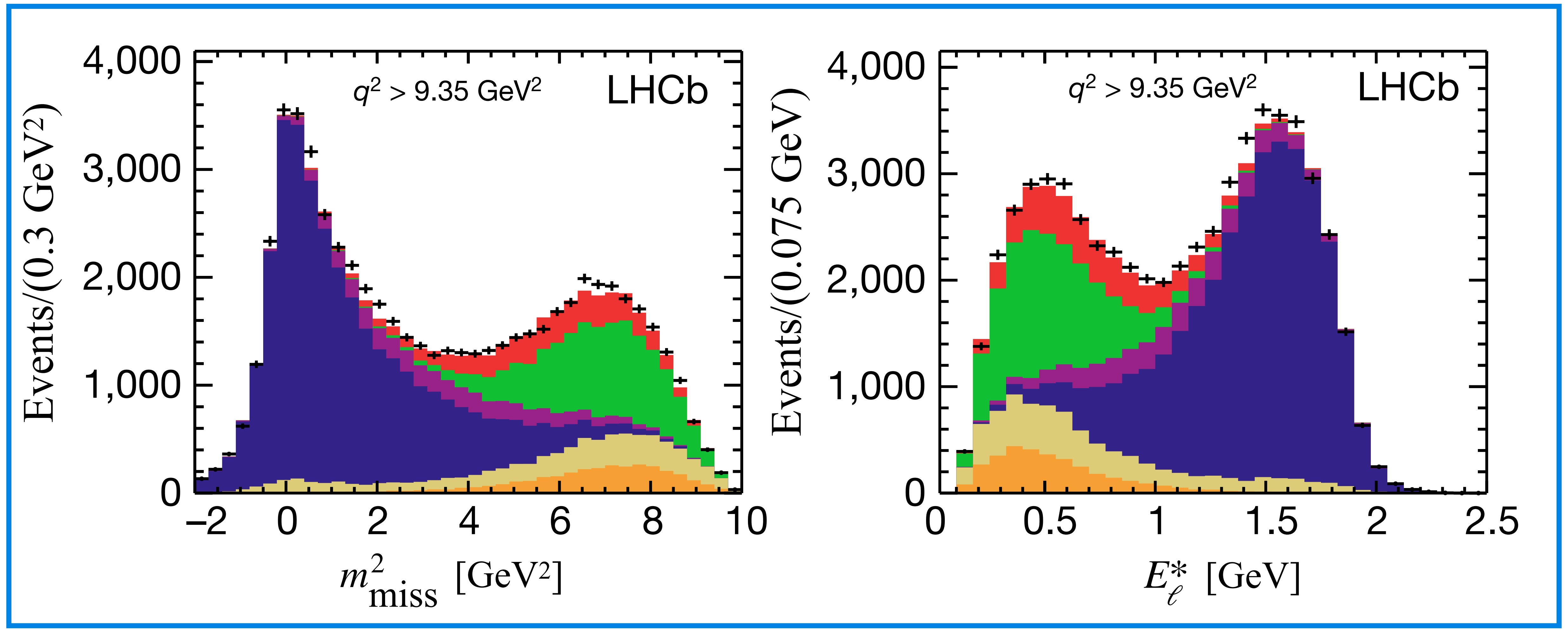
Muonic $\mathscr{R}(D^{*+})$ control samples

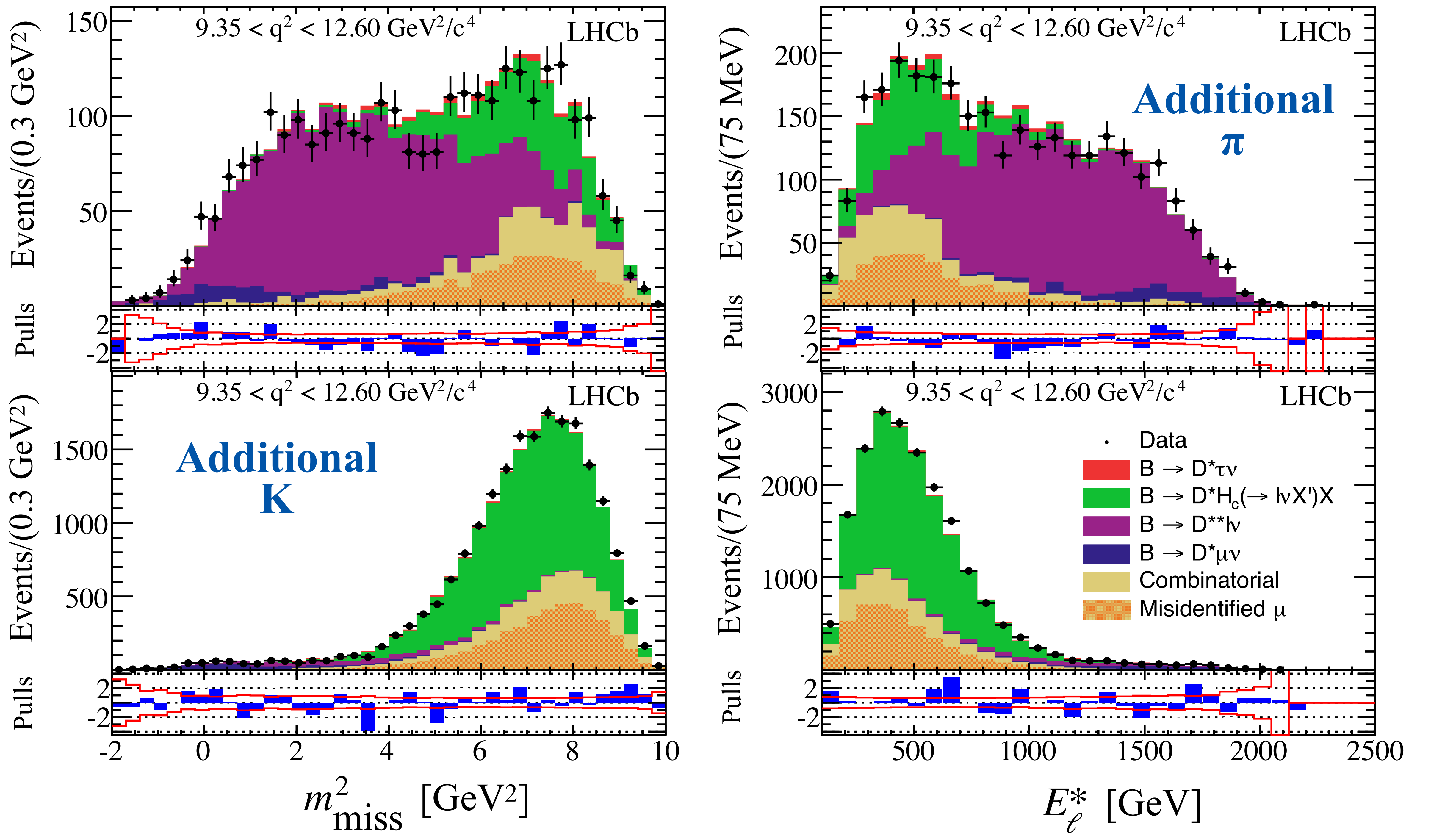
Phys. Rev. Lett. **115**, 111803 (2015)





- **Control samples instrumental** to determine bkgs.
  - Additional K: $B \to D^* H_c X$
  - Additional π: $B \to D^{**}(\to D^*\pi)\,\ell\nu$
  - Additional ππ: $B \to D^{**}(\to D^*\pi\pi)\,\ell\nu$





Muonic $\mathcal{R}(D^{*+})$ systematics

Contribution	Uncert. [%]
Simulated sample size	6.2
Misidentified μ bkg.	4.8
$\overline{B} \to D^{**}(\ell^-/\tau^-)\overline{\nu}$ bkg.	2.1
Signal/norm. FFs	1.9
Hardware trigger	1.8
DD bkg.	1.5
MC/data correction	1.2
Combinatorial bkg.	0.9
PID	0.9
Total systematic	**8.9**
Total statistical	**8.0**
Total	**12.0**

FastSim gives a **factor of 10×**, which **only covers Run 2**
Hopefully will scale with data, but it will require **faster FastSim, faster hardware progress, or more restrictive generator cuts**

Data driven procedure developed for $\mathcal{R}(J/\Psi)$ **will** reduce it to **less than 2%** in updated measurement

Primarily data driven

Disappears in Run 3

Primarily data driven

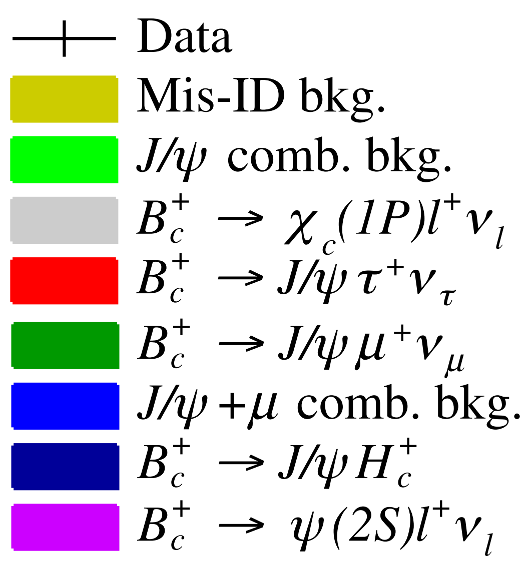
Primarily data driven

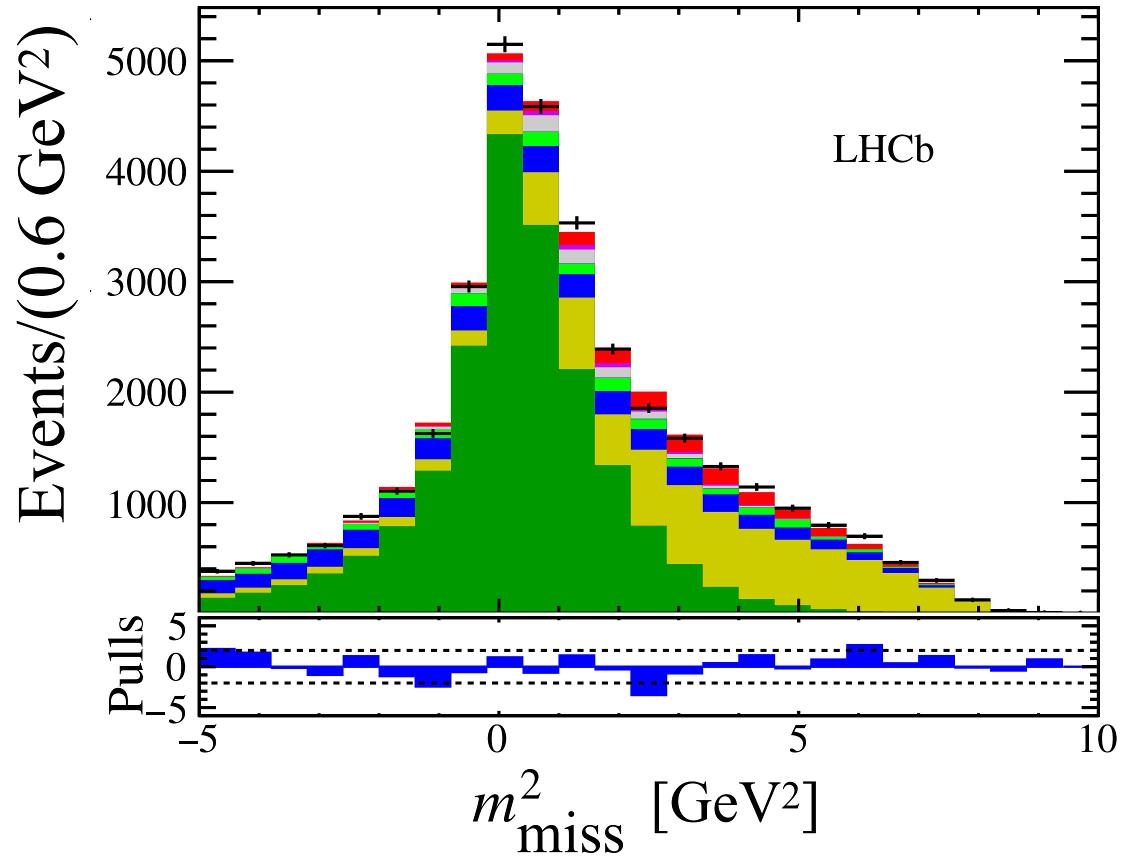
Note that only 30% of the systematic uncertainty is multiplicative, so the majority does not scale with central value

Generally, **systematic uncertainties** will **come down with data**, but there will probably be a **0.5-3% systematics floor** from the extrapolations to signal region and certain assumptions

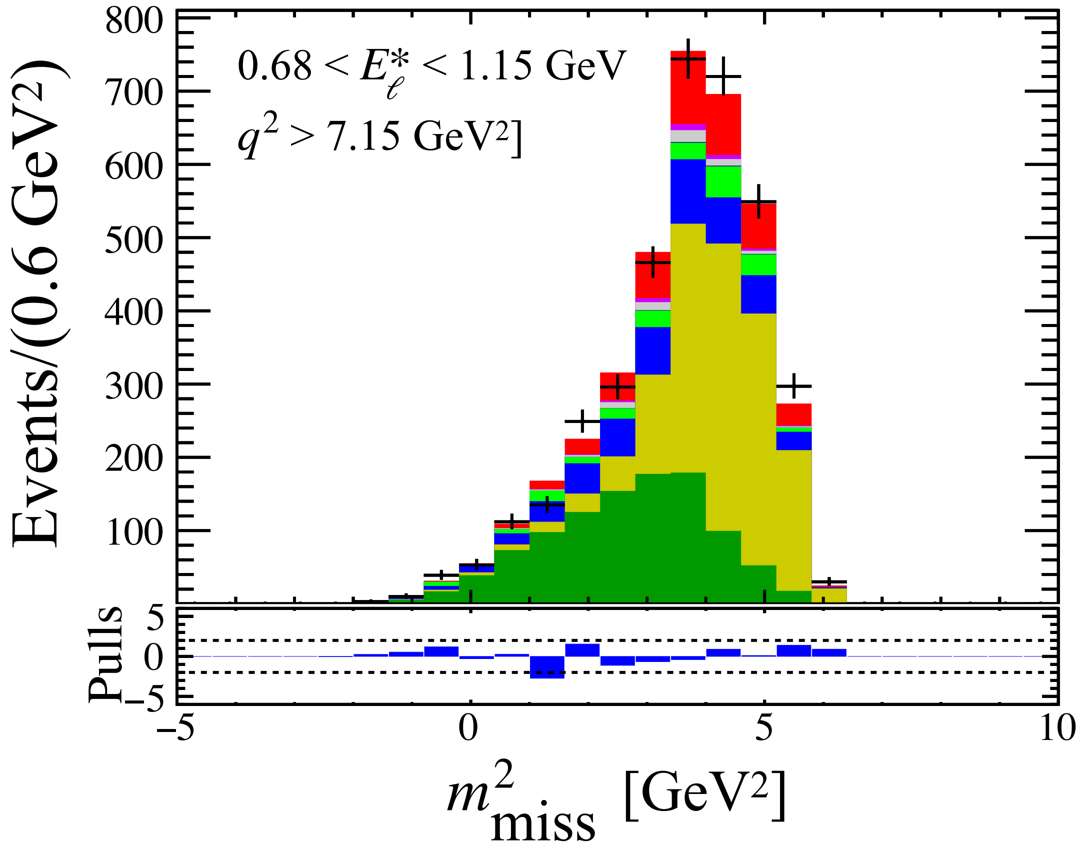
Muonic $\mathcal{R}(J/\Psi)$

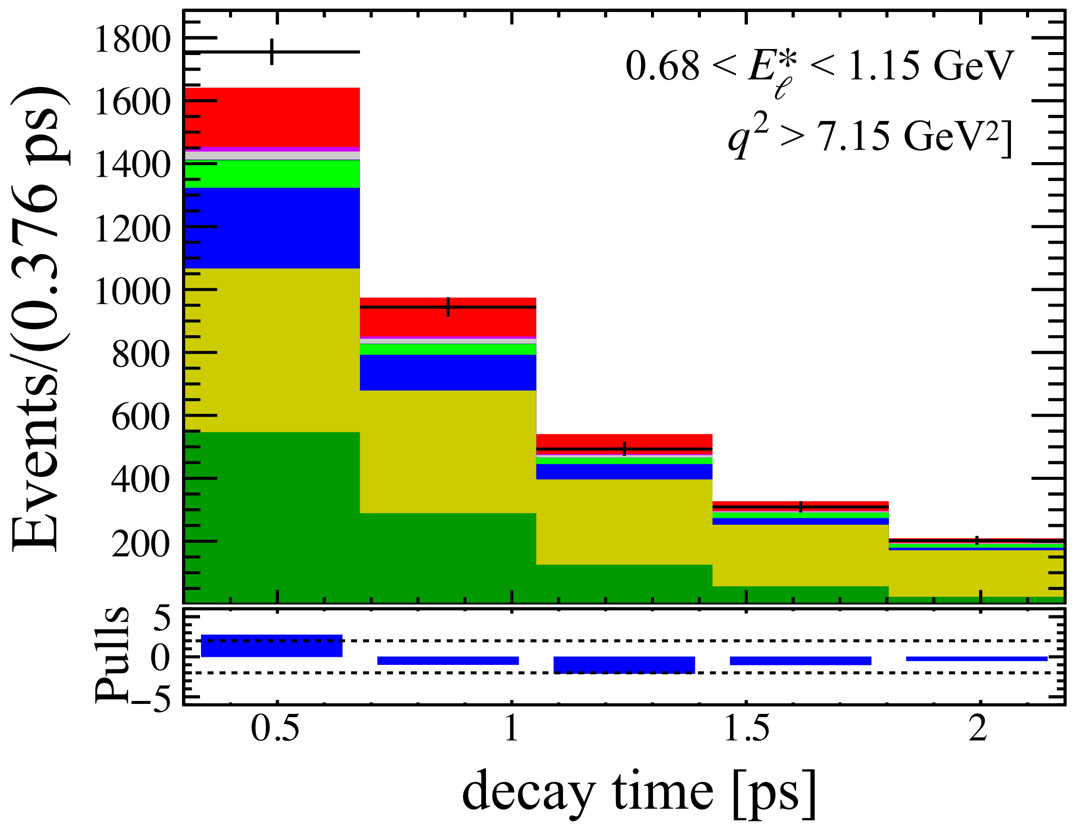
$$\mathcal{R}\left(J/\Psi\right) = \frac{\mathcal{B}\left(\bar{B}_c \to J/\Psi\tau\nu_\tau\right)}{\mathcal{B}\left(\bar{B}_c \to J/\Psi\mu\nu_\mu\right)}$$





Phys. Rev. Lett. **120**, 121801 (2018)





- Very similar strategy to muonic $\mathcal{R}(D^{*+})$
  - ➡ Add **decay time** to **separate B$_c$ from B$_{u,d}$**
  - ➡ **Main background** is **muon misID**

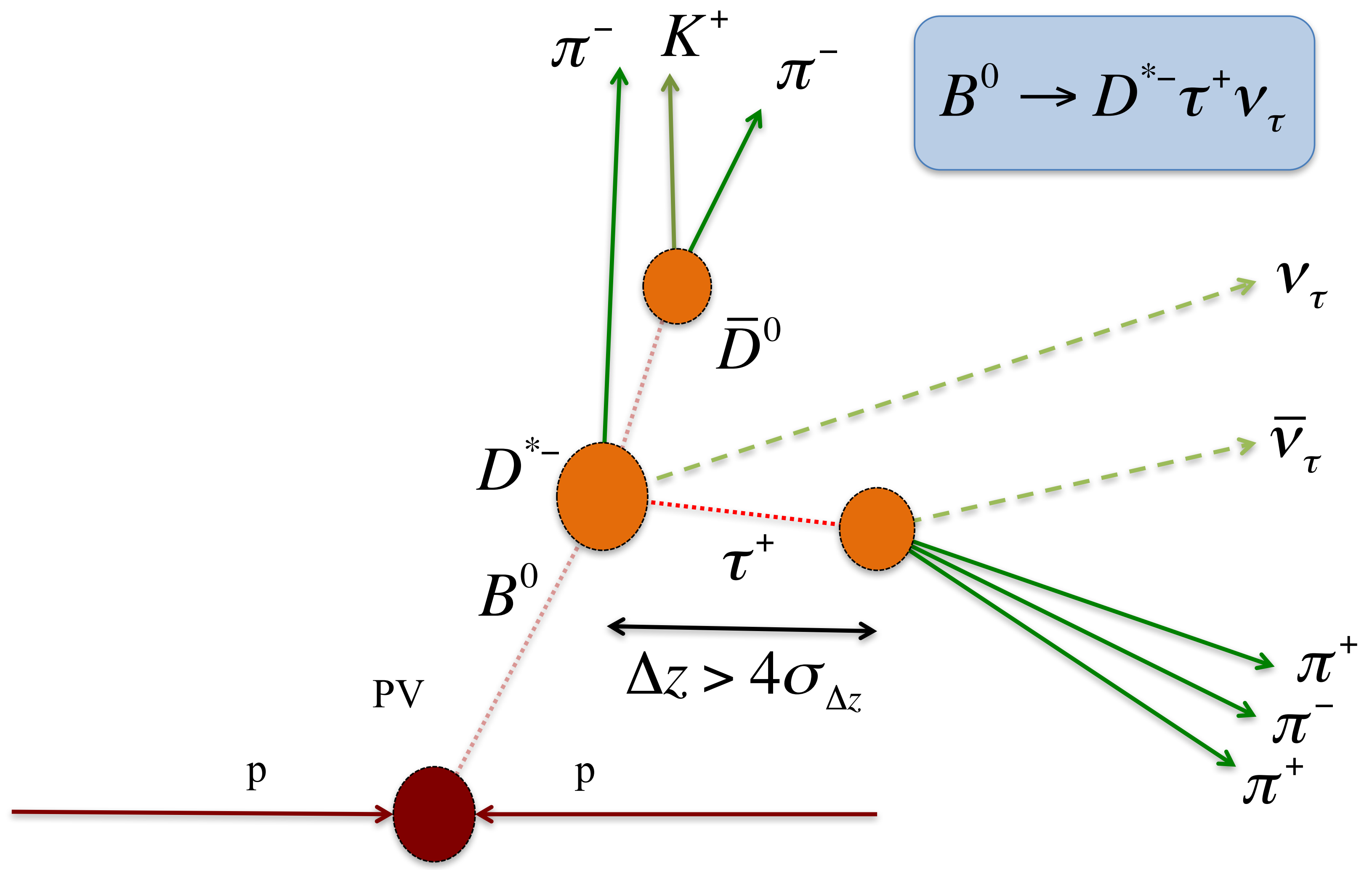
	Contribution	Uncert. [%]
LQCD calculation already helps	Signal/norm. FFs	17.0
Hopefully will scale with data	Simulated sample size	11.3
Will come down with more robust fit	Fit model	11.2
Primarily data driven	Misidentified μ bkg.	7.9
	Partial B_c bkg.	6.9
	Combinatorial bkg.	6.5
	$\epsilon_{\rm sig}/\epsilon_{\rm norm}$	0.9
	Total systematic	**25.4**
	Total statistical	**23.9**
	Total	**34.9**

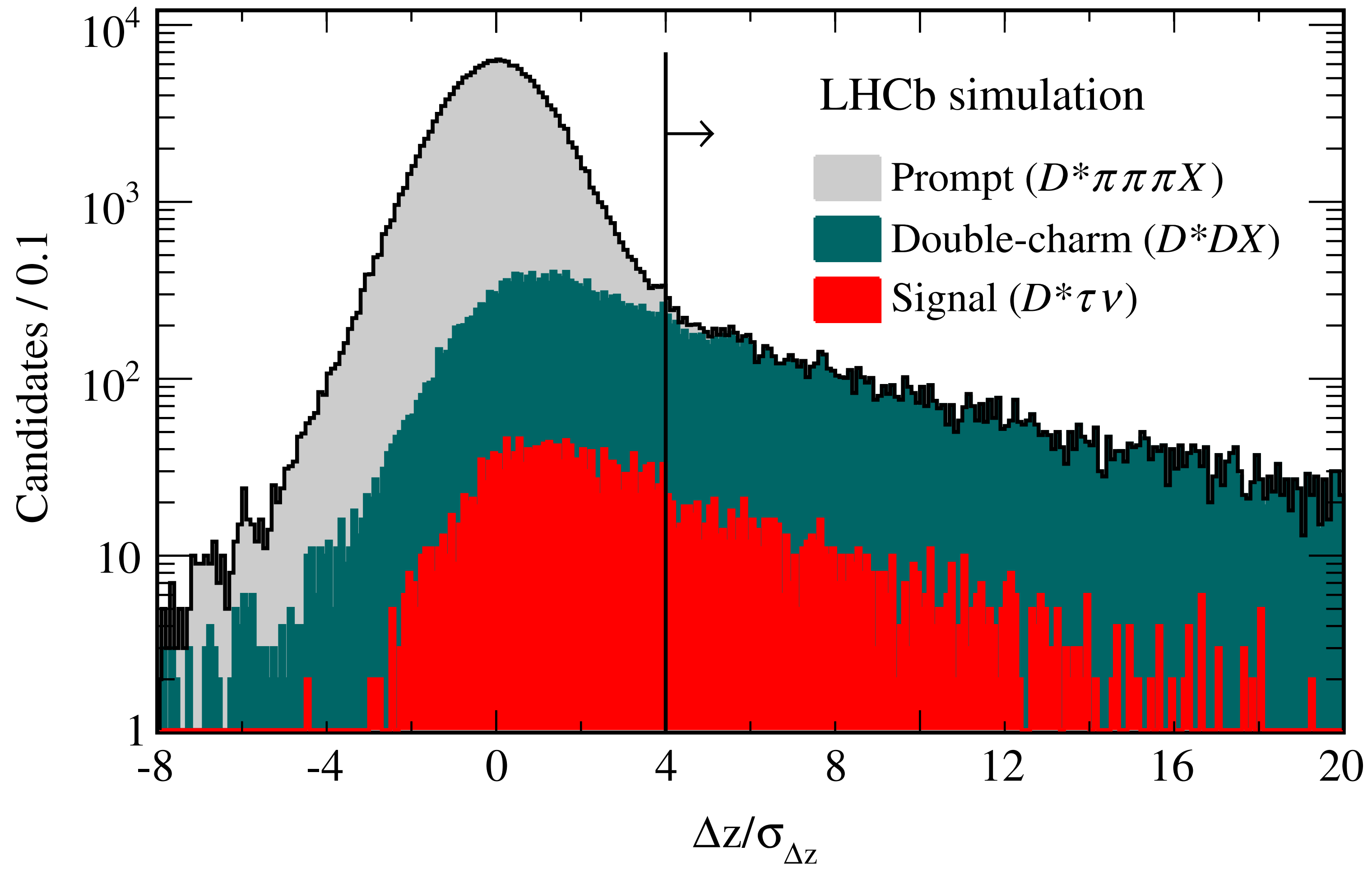
Expect a larger **1-5% floor** from difficulty of measuring FFs

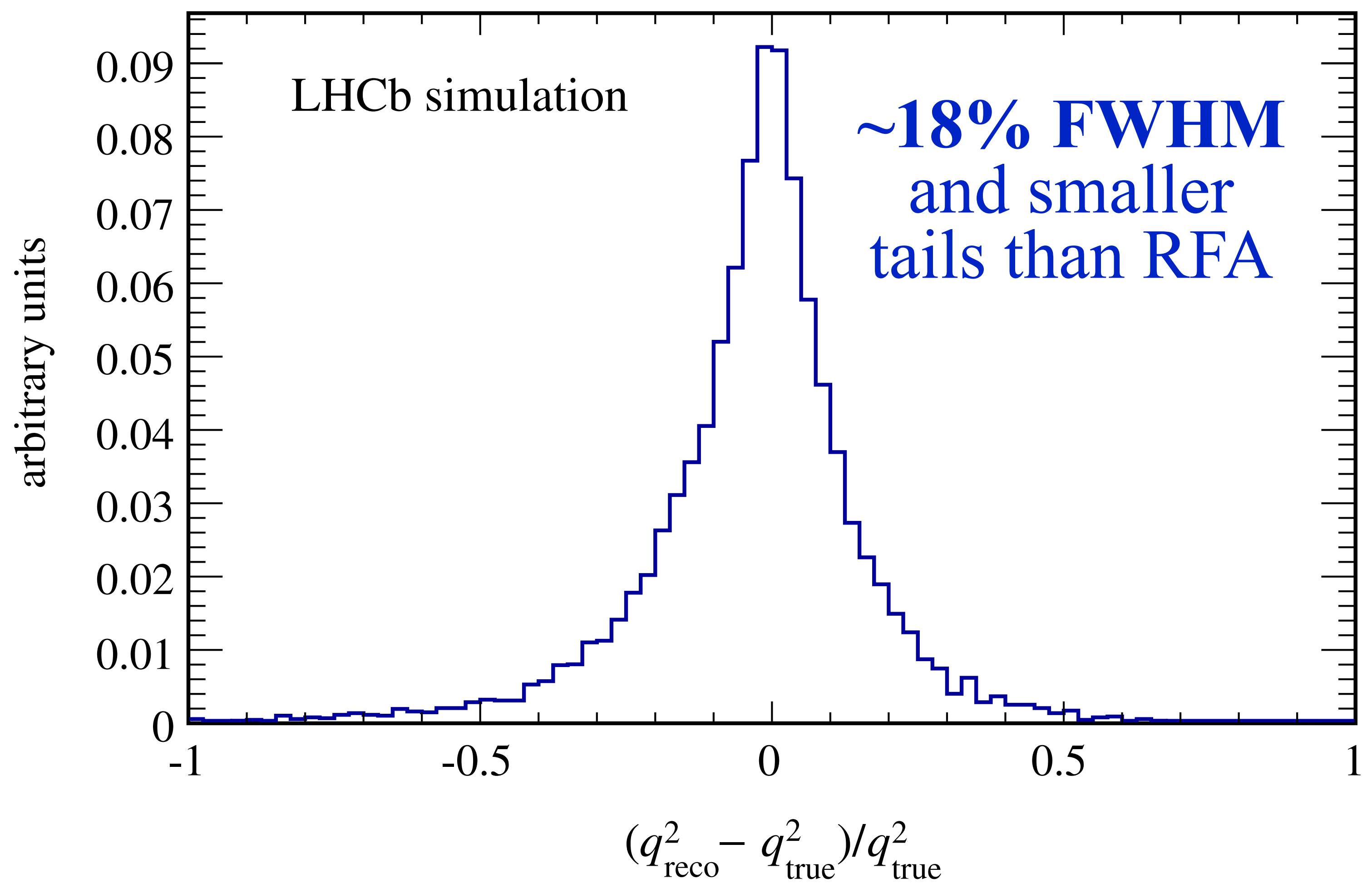
Hadronic* $\mathscr{R}(D^{*+})$

- Leverages **additional vertex** when $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ is used
  - **Main background** prompt $B \to D^*\pi\pi\pi X$ **reduced by 10⁴** with **τ flight distance**
  - **Better q^2** and **m^2_{miss} resolution** thanks to more precise determination of B momentum

Phys. Rev. D **97**, 072013 (2018)







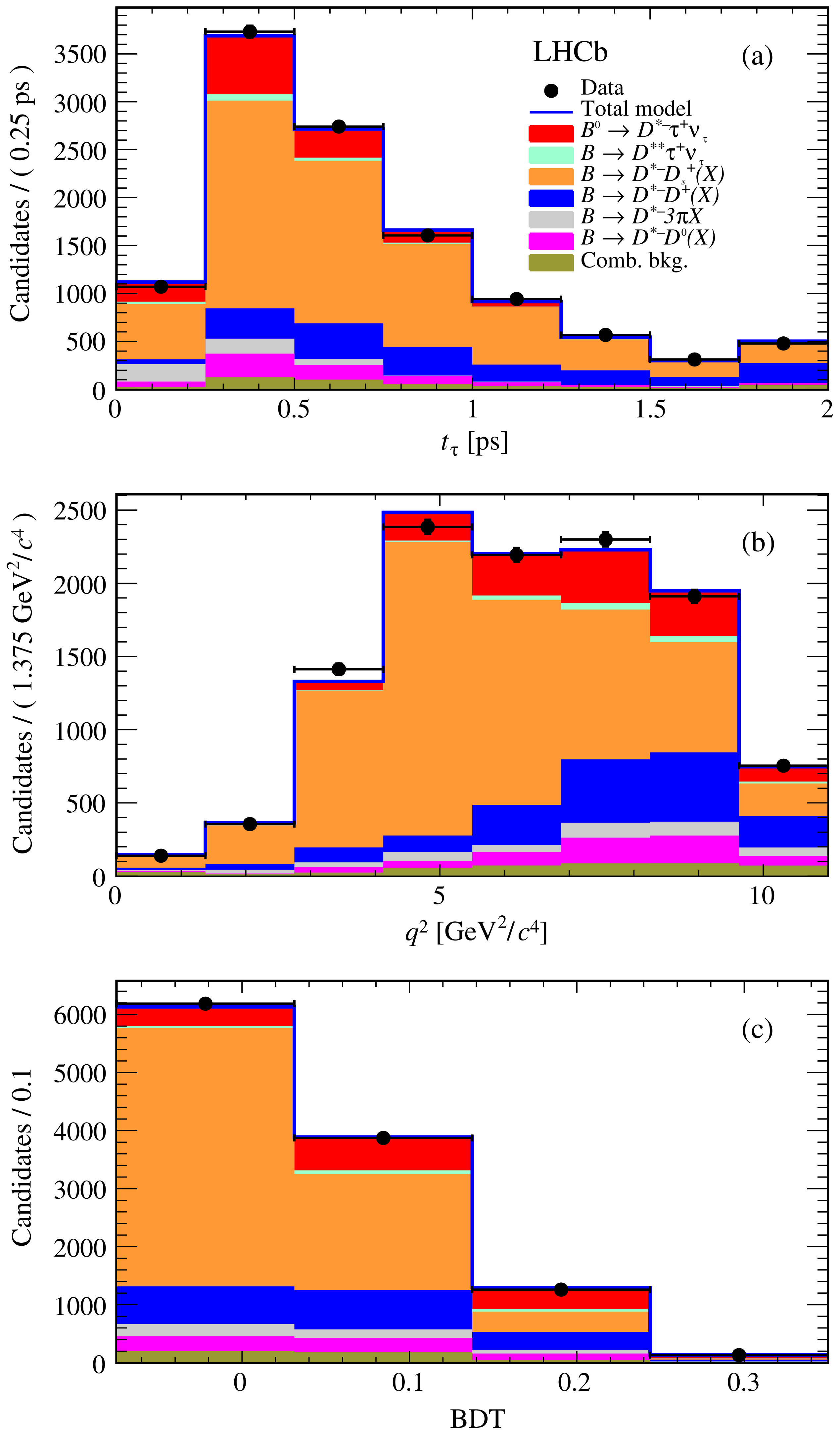
$$\mathscr{R}(D^*) = \boxed{\frac{\mathscr{B}\left(\bar{B} \to D^*\tau\nu_\tau\right)}{\mathscr{B}\left(\bar{B} \to D^*\pi\pi\pi\right)}} \times \boxed{\frac{\mathscr{B}\left(\bar{B} \to D^*\pi\pi\pi\right)}{\mathscr{B}\left(\bar{B} \to D^*\mu\nu_\mu\right)}}$$

Measure this ratio

$\mathscr{R}(D^{*+})$ depends on external branching fractions

*Actually, the $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ decay is semileptonic

Hadronic* $\mathscr{R}(D^{*+})$ systematics



- Similarly to previous measurements, **many systematic uncertainties** are expected to **scale down with data**
- However, **a floor of ~3-4% is more likely** due to dependence from **external branching fraction measurements**

Phys. Rev. D **97**, 072013 (2018)

Contribution	Uncert. [%]
DD bkg.	5.4
Simulated sample size	4.9
MC/data correction	3.7
$\overline{B} \to D^{**}(\ell^-/\tau^-)\overline{\nu}$ bkg.	2.7
Trigger	1.6
PID	1.3
Signal/norm. FFs	1.2
Combinatorial bkg.	0.7
τ decay	0.4
Total systematic	**9.0**
$\mathcal{B}(B \to D^*\pi\pi\pi)$	3.9
$\mathcal{B}(B \to D^*\mu\nu)$	2.0
$\mathcal{B}(\tau^+ \to 3\pi\nu)/\mathcal{B}(\tau^+ \to 3\pi\pi^0\nu)$	0.7
Total external	**4.4**
Total statistical	**6.5**
Total	**12.0**

*Actually, the $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ decay is semileptonic

Muonic vs Hadronic τ decay

- Run 1 measurements show key features of future LHCb LUV possibilities
  - Dominated by systematics, but will scale with data for the most part

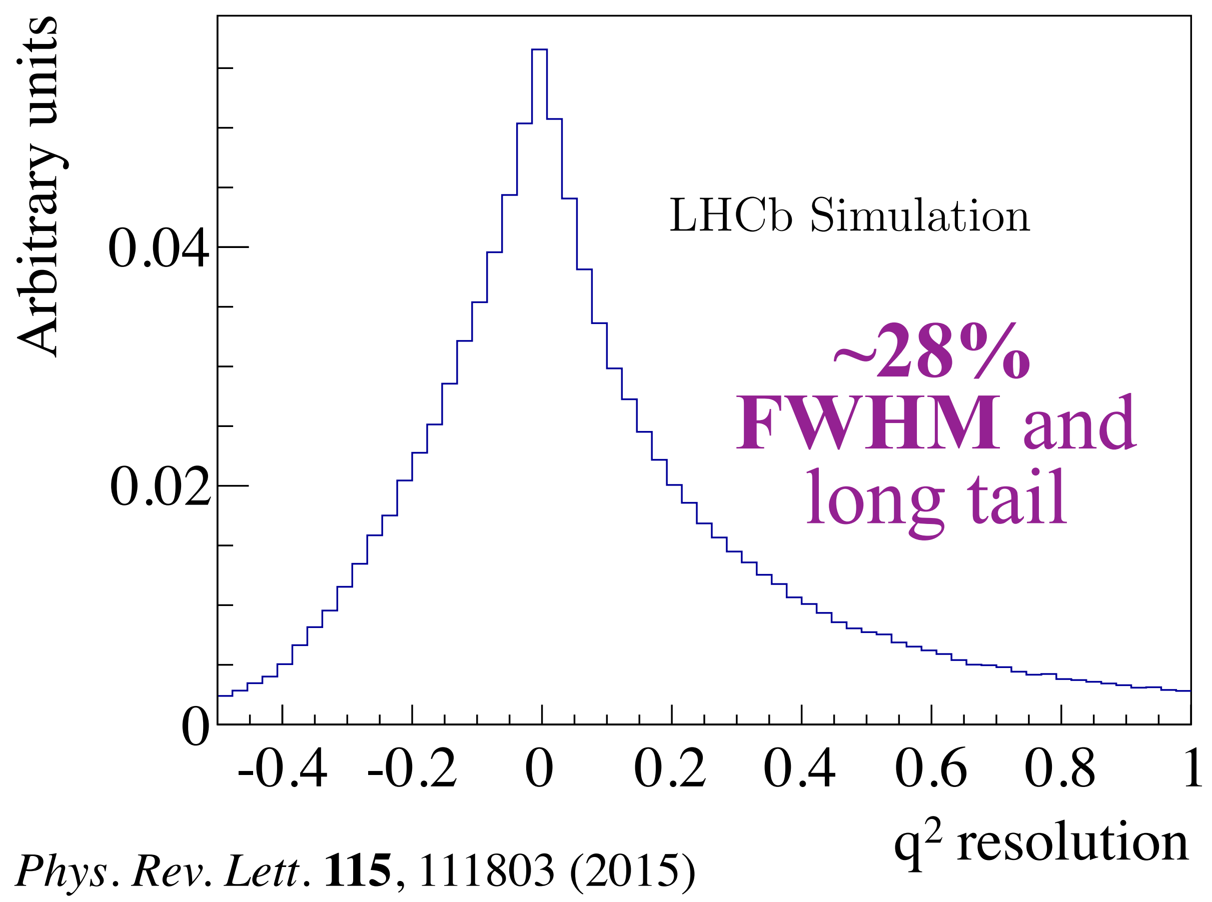
Note that the majority of the uncertainty does not scale with central value

Muonic $\mathcal{R}(D^{*+})$	Uncert. [%]
Total systematic	**8.9**
Total statistical	**8.0**
Total	**12.0**

Systematics floor probably 0.5-3%

Muonic $\mathcal{R}(J/\Psi)$	Uncert. [%]
Total systematic	**25.4**
Total statistical	**23.9**
Total	**34.9**

Systematics floor 1-5% due to FFs



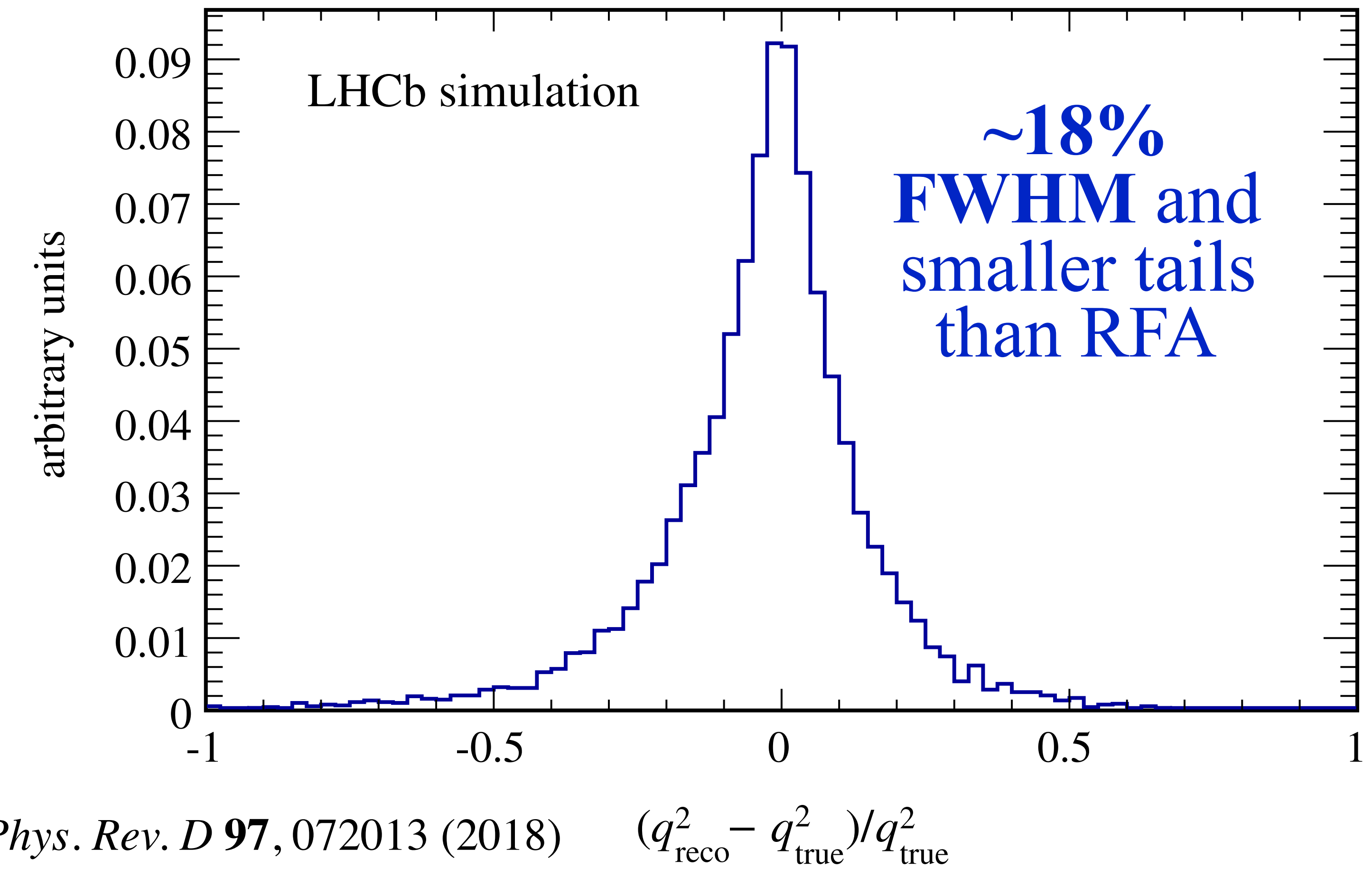
Phys. Rev. Lett. **115**, 111803 (2015)

Muonic decays of τ allow for **precise determinations** of $\mathscr{R}(X_c)$ at higher stats

Hadronic $\mathcal{R}(D^{*+})$	Uncert. [%]
Total systematic	**9.0**
Total external	**4.4**
Total statistical	**6.5**
Total	**12.0**

Systematics floor 3-4% due to BF_{ext}

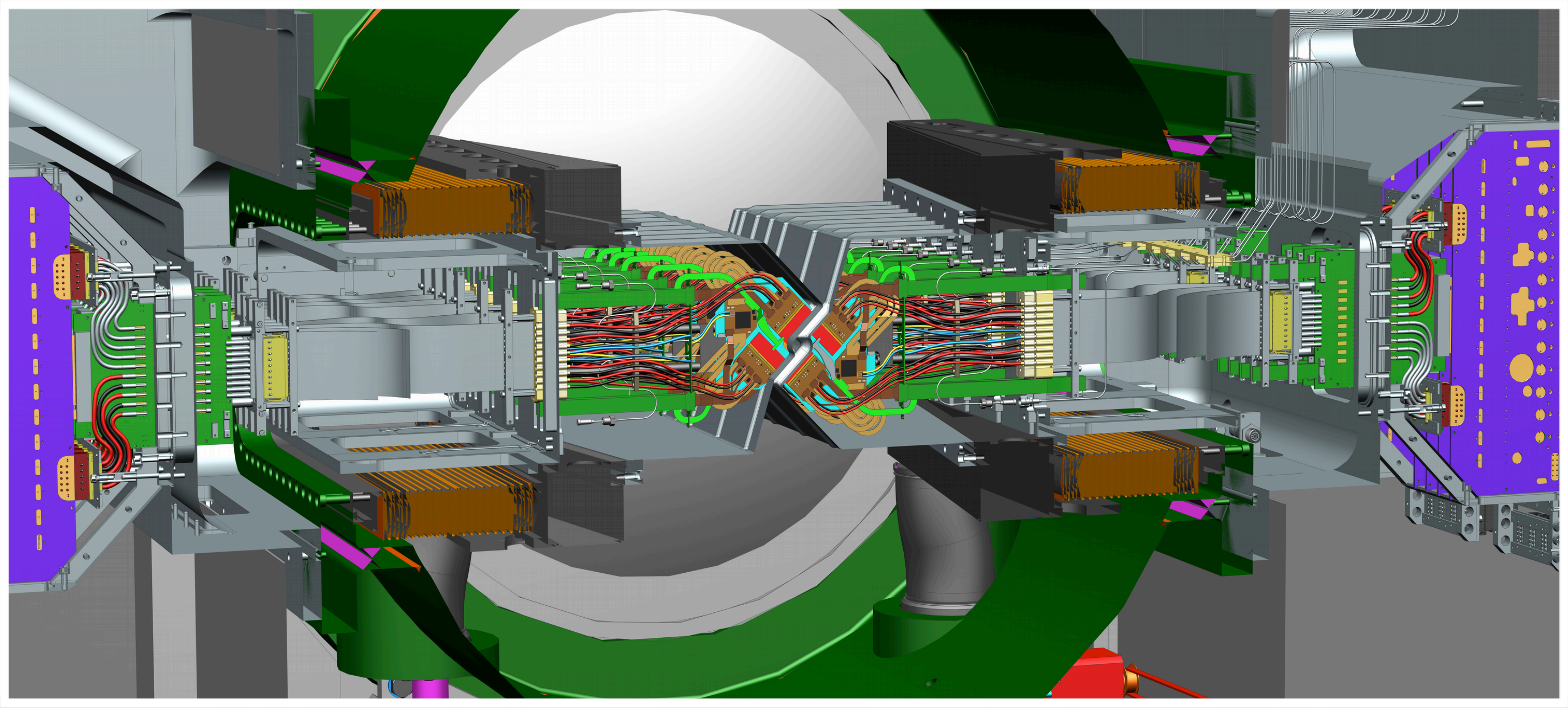
$\mathscr{R}(X_c)$ precision with **hadronic** decays of τ may be limited by external measurements



Phys. Rev. D **97**, 072013 (2018)

But may allow for **better measurements** of **kinematic distributions**

Prospects for charged LUV at LHCb



The new pixel VELO will help a lot!

Upcoming measurements

- Analyses at an advanced stage
  - Run 1 muonic $\mathscr{R}(D^0) - \mathscr{R}(D^*)$
  - Hadronic $\mathscr{R}(D^{**})$

B^0, B^+

B_s^0

B_c^+

Λ_b^0

- Analyses in early to very early stages primarily using Run 2
  - Run 2 muonic $\mathscr{R}(D^0) - \mathscr{R}(D^*)$, muonic $\mathscr{R}(D^+) - \mathscr{R}(D^{*+})$
  - Run 2 hadronic $\mathscr{R}(D^{*+})$, hadronic $\mathscr{R}(D^0) - \mathscr{R}(D^*)$, hadronic $\mathscr{R}(D^+) - \mathscr{R}(D^{*+})$
  - Muonic $\mathscr{R}(p\bar{p})$
  - Hadronic $B \to D^{*+}\tau\nu$ polarization of D* and τ
  - Muonic $B \to D^{*+}\tau\nu$ angular distributions
  - $\mathscr{R}(D^{*+})_{light}$
  - Muonic $\mathscr{R}(D_s) - \mathscr{R}(D_s^*)$, hadronic $\mathscr{R}(D_s) - \mathscr{R}(D_s^*)$
  - Run 2 muonic $\mathscr{R}(J/\Psi)$, hadronic $\mathscr{R}(J/\Psi)$
  - Muonic $\mathscr{R}(\Lambda_c)$, hadronic $\mathscr{R}(\Lambda_c)$

Some of these may take several years, but **aim to cover as many observables as possible**

Assumptions on evolution of $\mathscr{R}(X_c)$

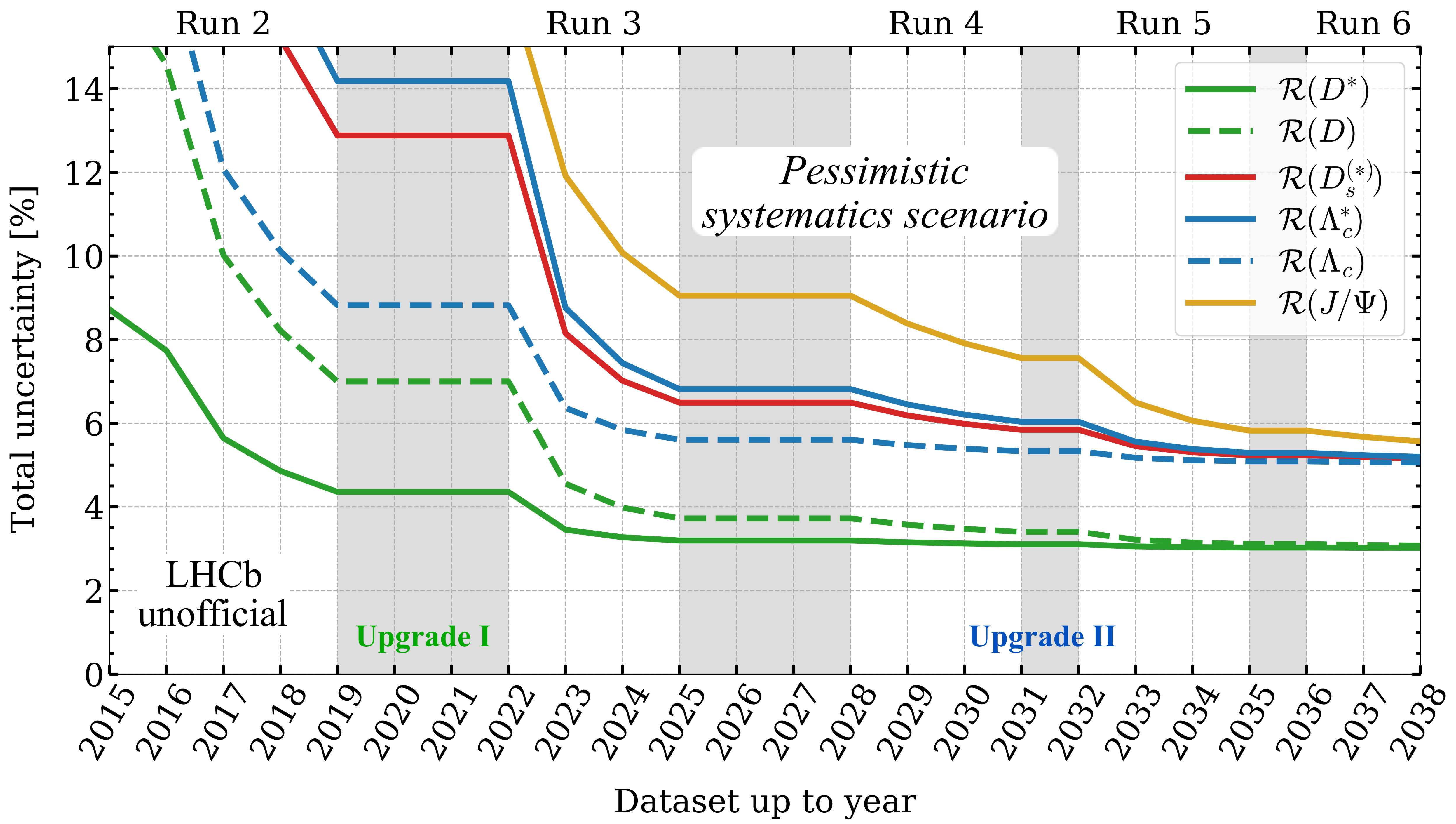
Run 1		LS1		Run 2				LS2			Run 3			LS3			Run 4			LS4	Run 5			LS5	Run 6		
2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	
1.1	2.0	-	-	0.3	1.7	1.7	2.2	-	-	-	8.3	8.3	8.3	-	-	-	8.3	8.3	8.3	-	50	50	50	-	50	50	fb^{-1}

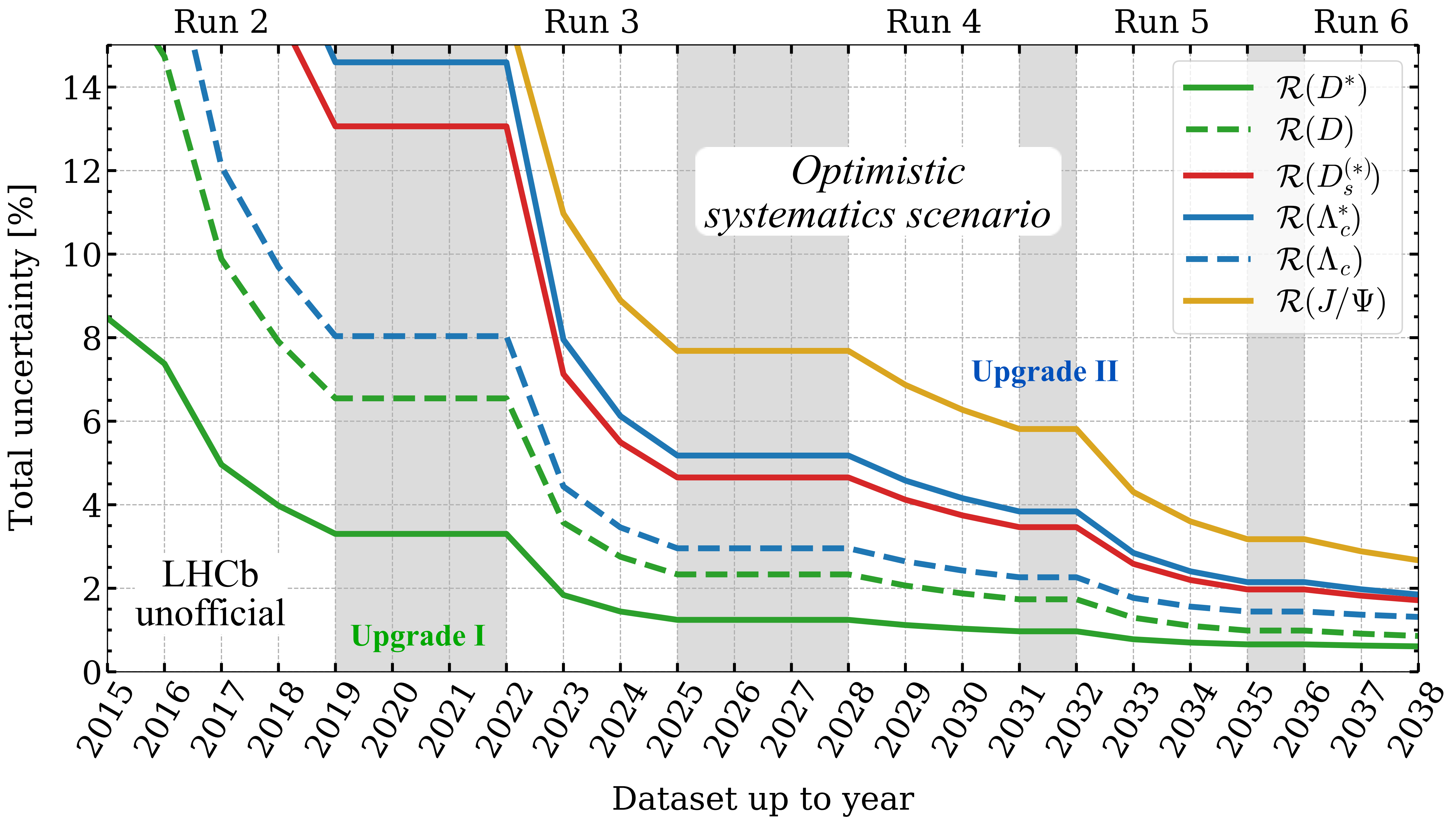
- **Extrapolate $\mathscr{R}(D^*)$** based on Run 1 muonic $\mathscr{R}(D^{*+})$ **assuming**
  - **2×** more stats starting in **Run 1** from **adding $\mathscr{R}(D^{*0})$**
  - **3×** more stats starting in **Run 2** from **better HLT** (1.5×) and **cross section** (2×)
  - **2×** more stats starting in **Run 3** from **no hardware trigger**
  - **Systematics scale with data** but **floor** of **0.5%** (optimistic) **and 3%** (pessimistic)
- **Extrapolate $\mathscr{R}(J/\Psi)$** based on Run 1 muonic $\mathscr{R}(J/\Psi)$
  - **Systematics scale with data** but **floor** of **1%** (optimistic) **and 5%** (pessimistic)
- Estimate the other species based on $\mathscr{R}(D^*)$ extrapolation and
  - **1/4×** stats for $\mathscr{R}(D)$ from smaller BF and no feed-down
  - **1/16×** stats for $\mathscr{R}(D_s^{(*)})$ from $f_s/(f_u+f_d)$ and extra track (1/2×)
  - **1/6×** stats for $\mathscr{R}(\Lambda_c)$ from $f_{\Lambda_b}/(f_u+f_d)$ ~ 1/4, extra track (1/2×), and larger Λ_c BF
  - **1/20×** stats for $\mathscr{R}(\Lambda_c^*)$ from $f_{\Lambda_b}/(f_u+f_d)$ ~ 1/4, two slow pions and lower BF
  - **Systematics scale with data** but **floor** of **1%** (optimistic) **and 5%** (pessimistic) but for $\mathscr{R}(D)$ same as $\mathscr{R}(D^*)$

Rough assumptions based on BFs and fragmentation fractions and building on work from Patrick Owen

Prospects for $\mathcal{R}(X_c)$

- **Enormous improvement from Upgrade I** (Runs 3+4)
  - 50 fb^{-1} plus factor of two from no hardware trigger
- **After Upgrade II** (Runs 5+6) it **depends** on **systematics scenario**
  - **Significant gains** for $\mathcal{R}(J/\Psi)$, $\mathcal{R}(D_s^{(*)})$, and $\mathcal{R}(\Lambda_c^*)$ if we can control FF systematics



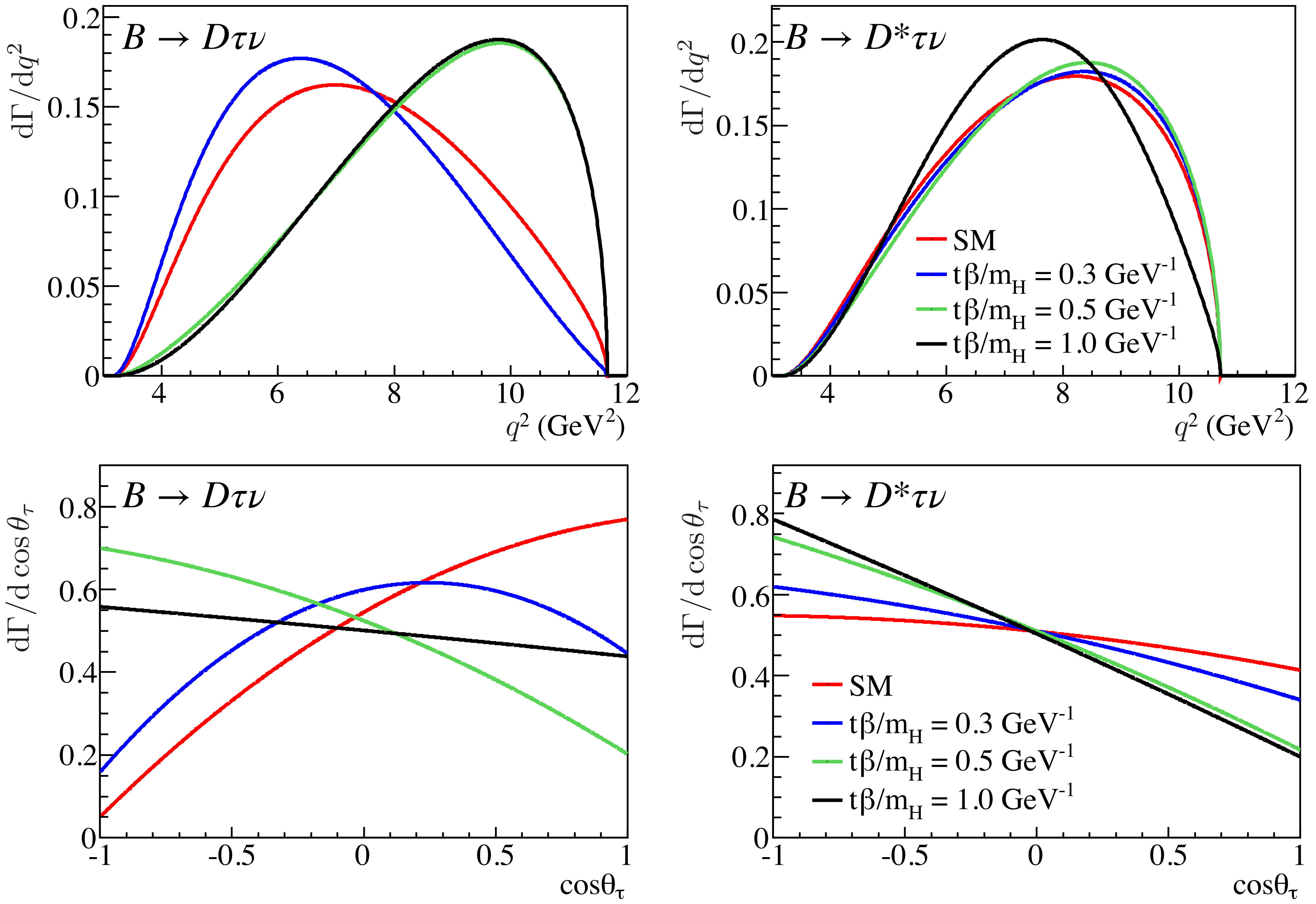


Measuring distributions

- Upgrades give **access kinematic distributions sensitive to NP**
  - ➡ Instrumental in characterizing any anomaly
  - ➡ Unique sensitivity to $B_s \to D_s^{(*)}\tau\nu$, $B_c \to J/\Psi\tau\nu$, and $\Lambda_b \to \Lambda_c\tau\nu$ (see following talk by A. Datta)

Impact of 2HDM on q² and $\theta_\tau = \pi - \theta_L$

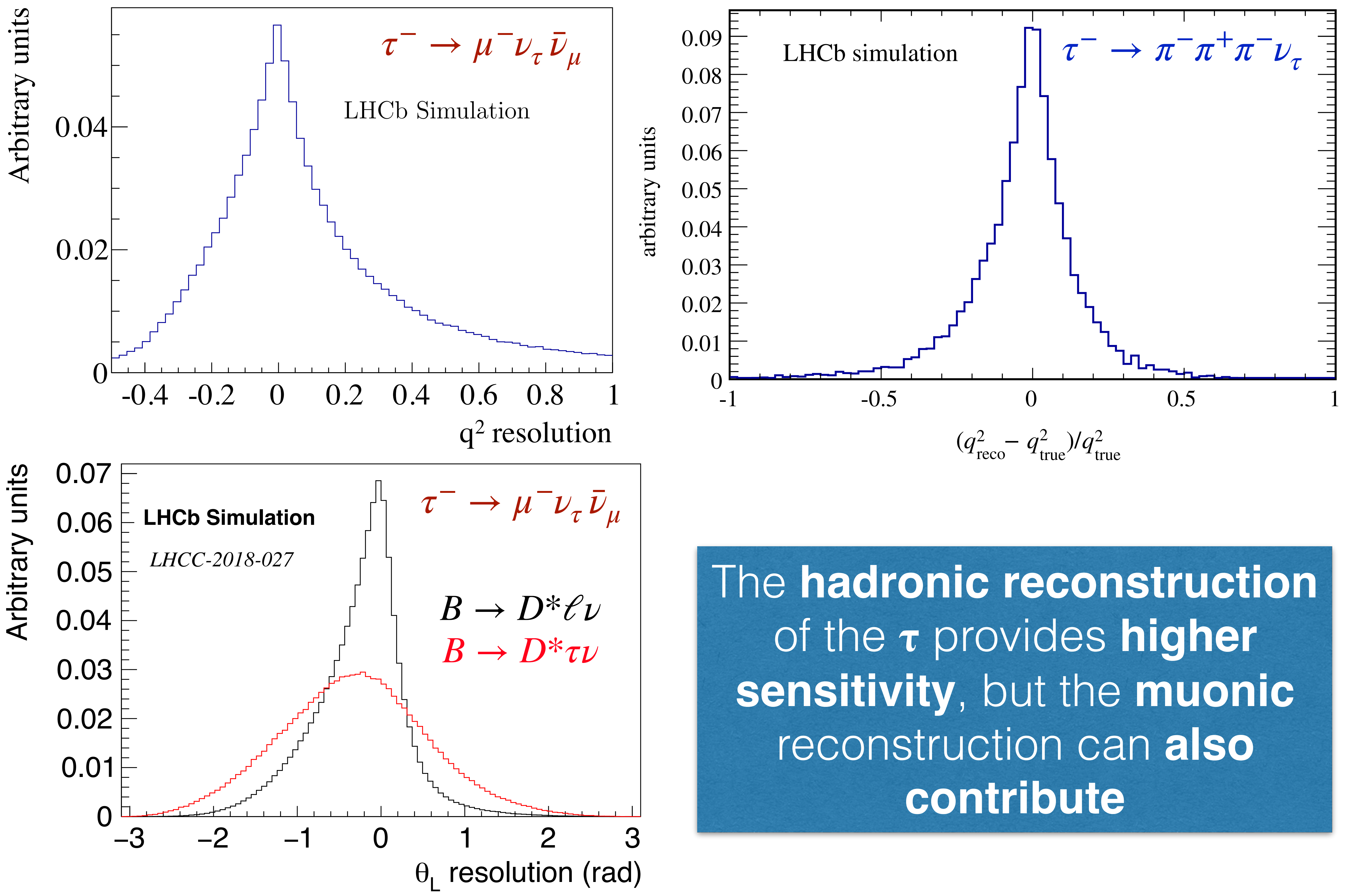
MFS "Evidence for an excess of $B \to D^{*+}\tau\nu$ decays" Dissertation, Stanford University (2012)



LHCb resolution on q² and θ_L

Phys. Rev. Lett. **115**, 111803 (2015)

Phys. Rev. D **97**, 072013 (2018)



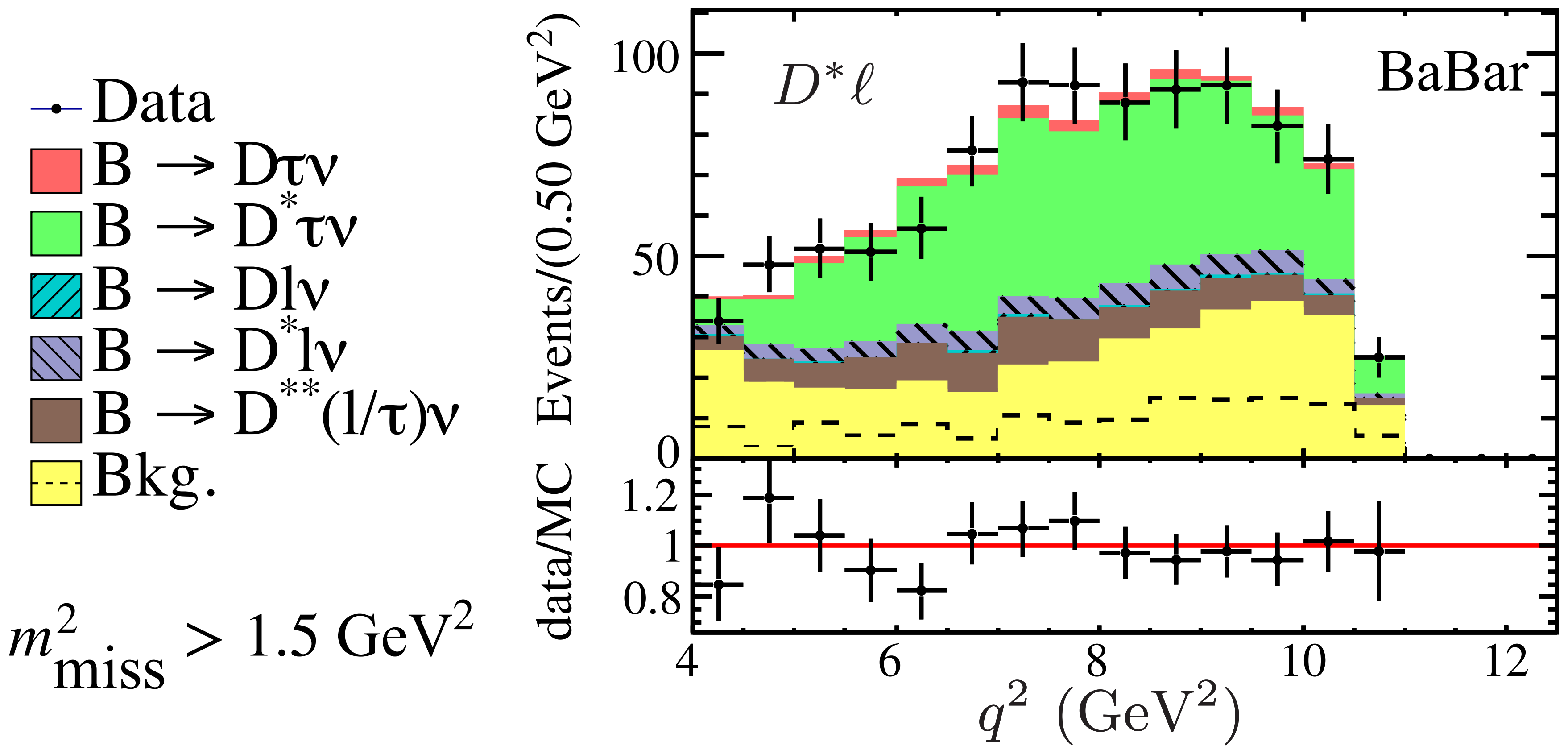
The **hadronic reconstruction** of the **τ** provides **higher sensitivity**, but the **muonic** reconstruction can **also contribute**

Challenges of measuring distributions at LHCb

- Larger backgrounds and lack of full event reconstruction make distributions **challenging**
  - ➡ Upgrade 2 samples may allow for techniques such as $B^*_{s2} \to B^+K^-$ tagging

Phys. Rev. D **88**, 072012 (2013)

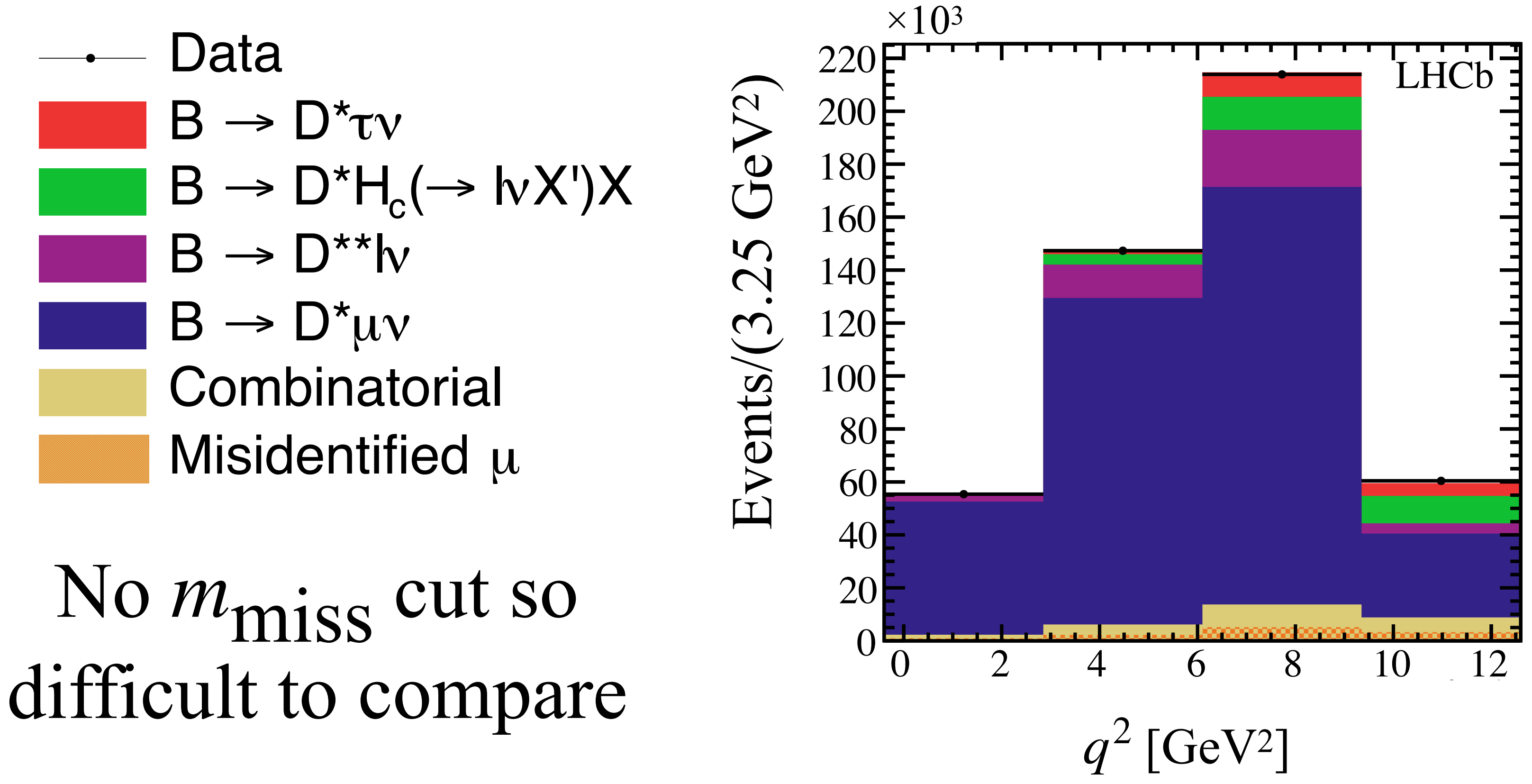
$\sigma_{\text{stat}}\left(\mathcal{R}(D^*)\right) = 7.1\,\%$



$m^2_{\text{miss}} > 1.5\ \text{GeV}^2$

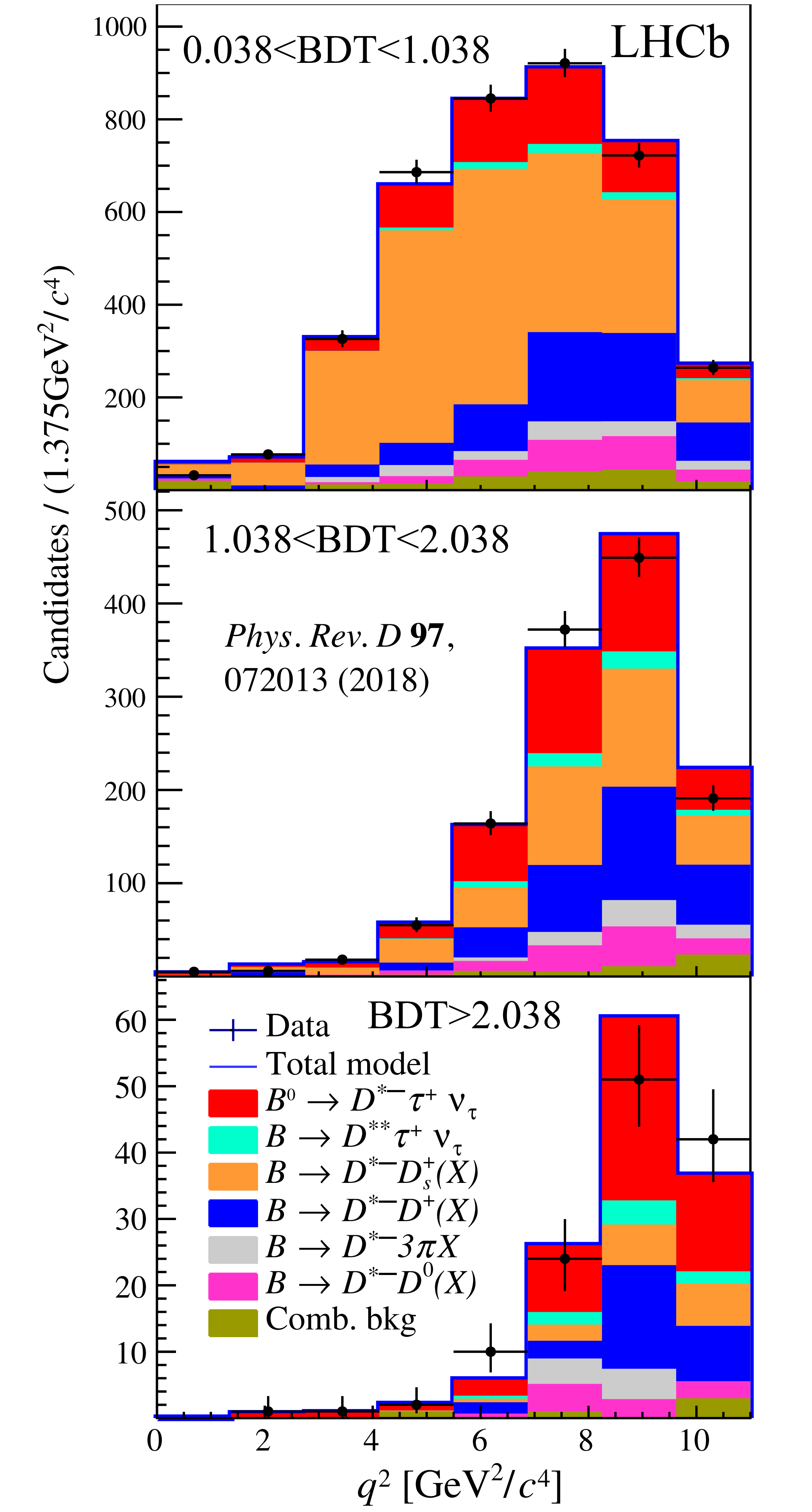
Phys. Rev. Lett. **115**, 111803 (2015)

$\sigma_{\text{stat}}\left(\mathcal{R}(D^*)\right) = 8.0\,\%$



No m_{miss} cut so difficult to compare

$\sigma_{\text{stat}}\left(\mathcal{R}(D^*)\right) = 6.4\,\%$

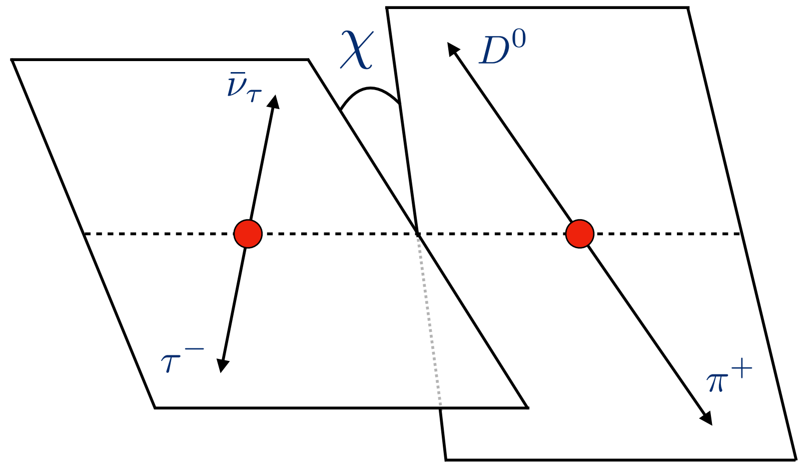


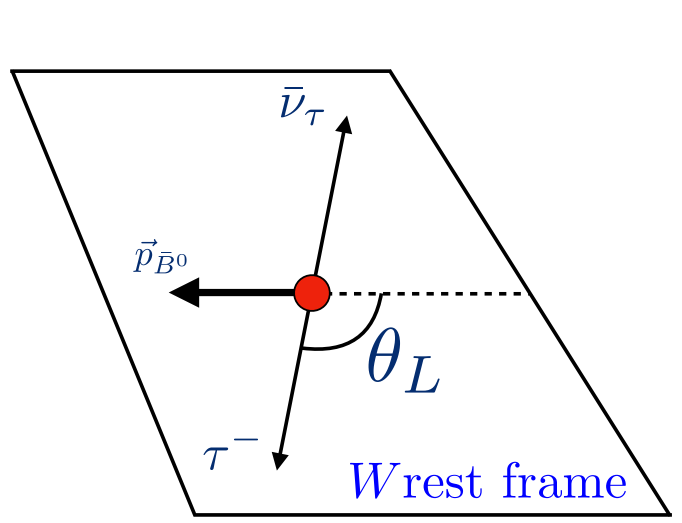
- **Run 1 hadronic measurement** already shows some **sensitivity to q² distribution**

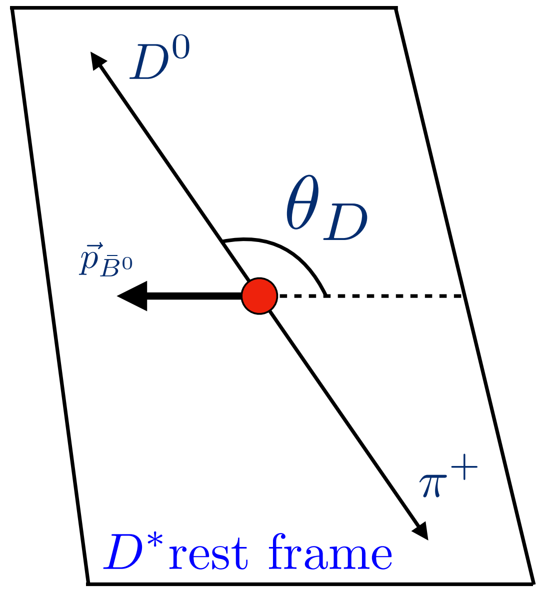
Possible sensitivity to angular distributions

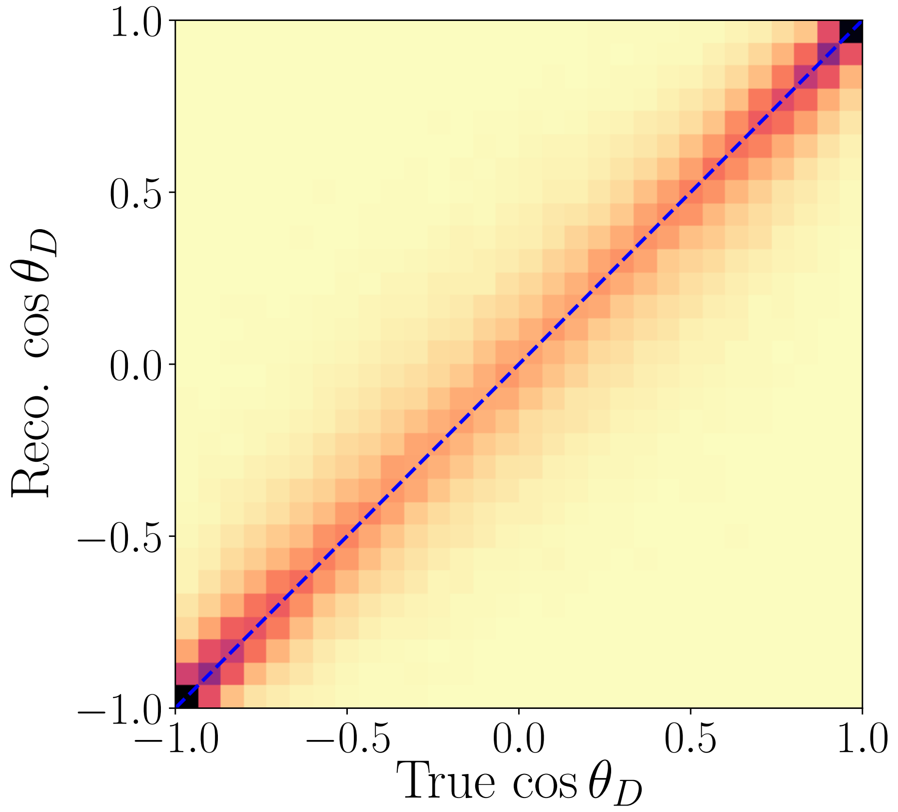
- Hadronic analyses expected to have good angular sensitivity
  - ➡ Hill, John, Ke, Poluektov, *JHEP* **2019**, 133 (2019) 1908.04643

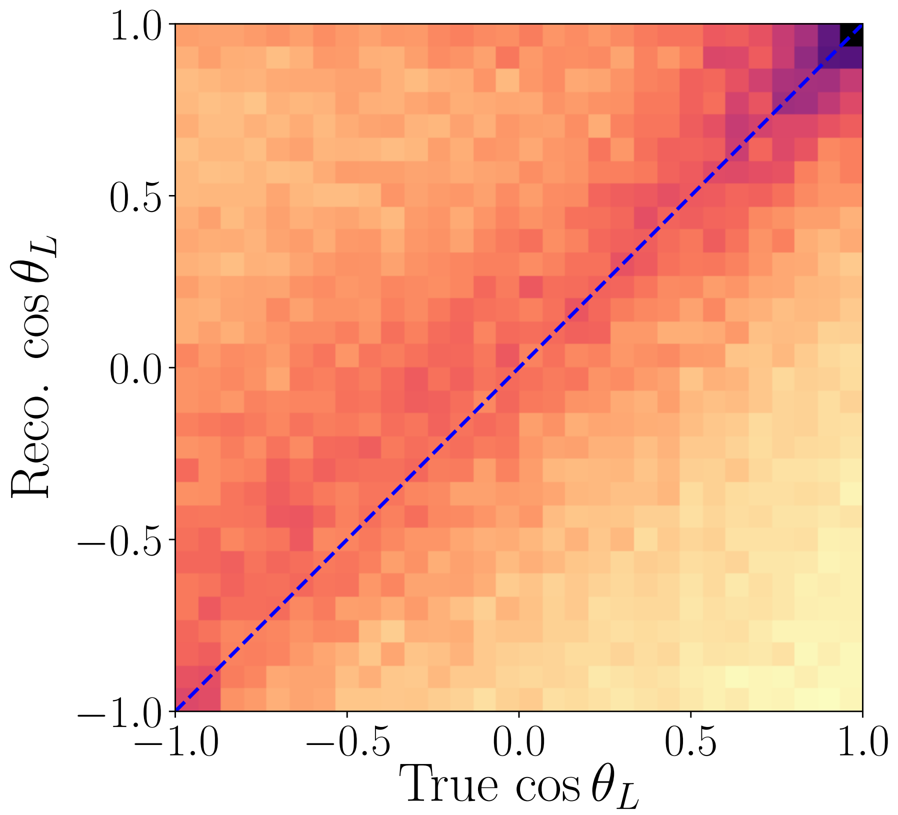
$$\frac{d^4\Gamma}{dq^2\, d(\cos\theta_D)\, d(\cos\theta_L)\, d\chi} \propto I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D$$
$$+ [I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L$$
$$+ [I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L$$
$$+ [I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D$$
$$+ [I_4\cos\chi + I_8\sin\chi]\sin 2\theta_L\sin 2\theta_D$$
$$+ [I_5\cos\chi + I_7\sin\chi]\sin\theta_L\sin 2\theta_D\,,$$

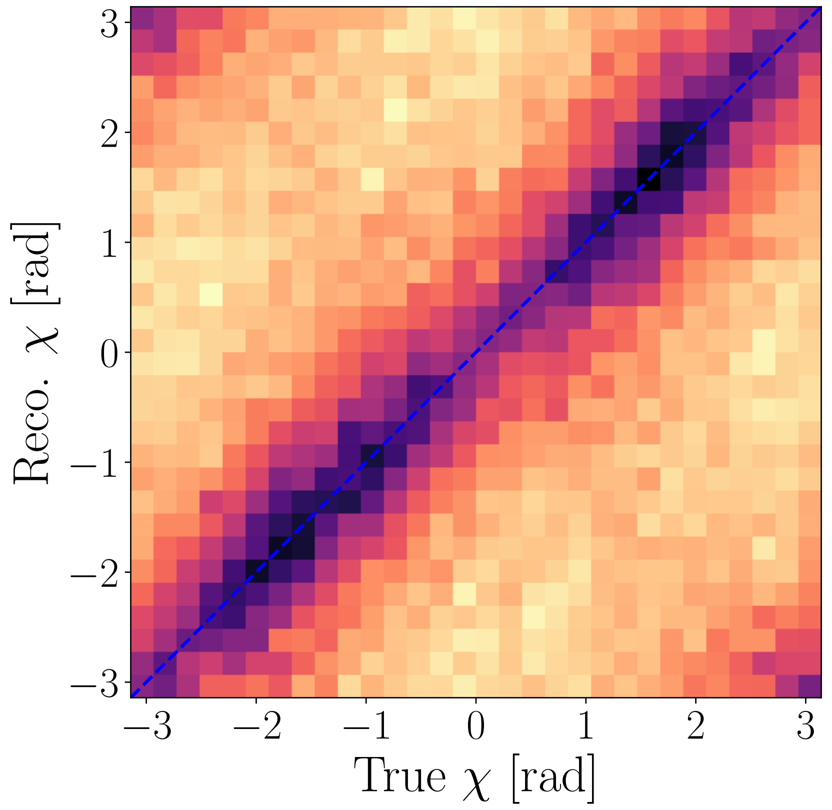


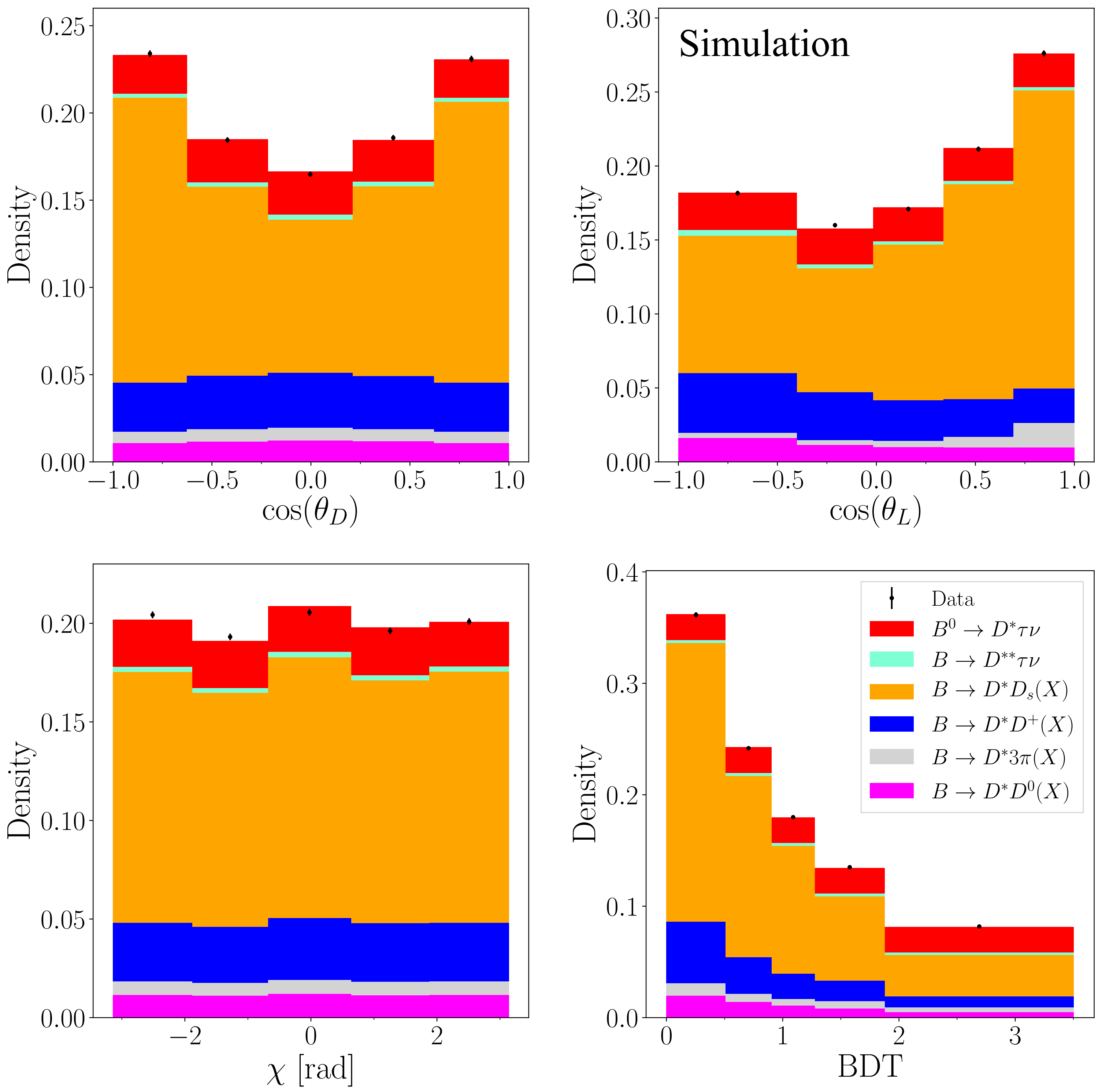


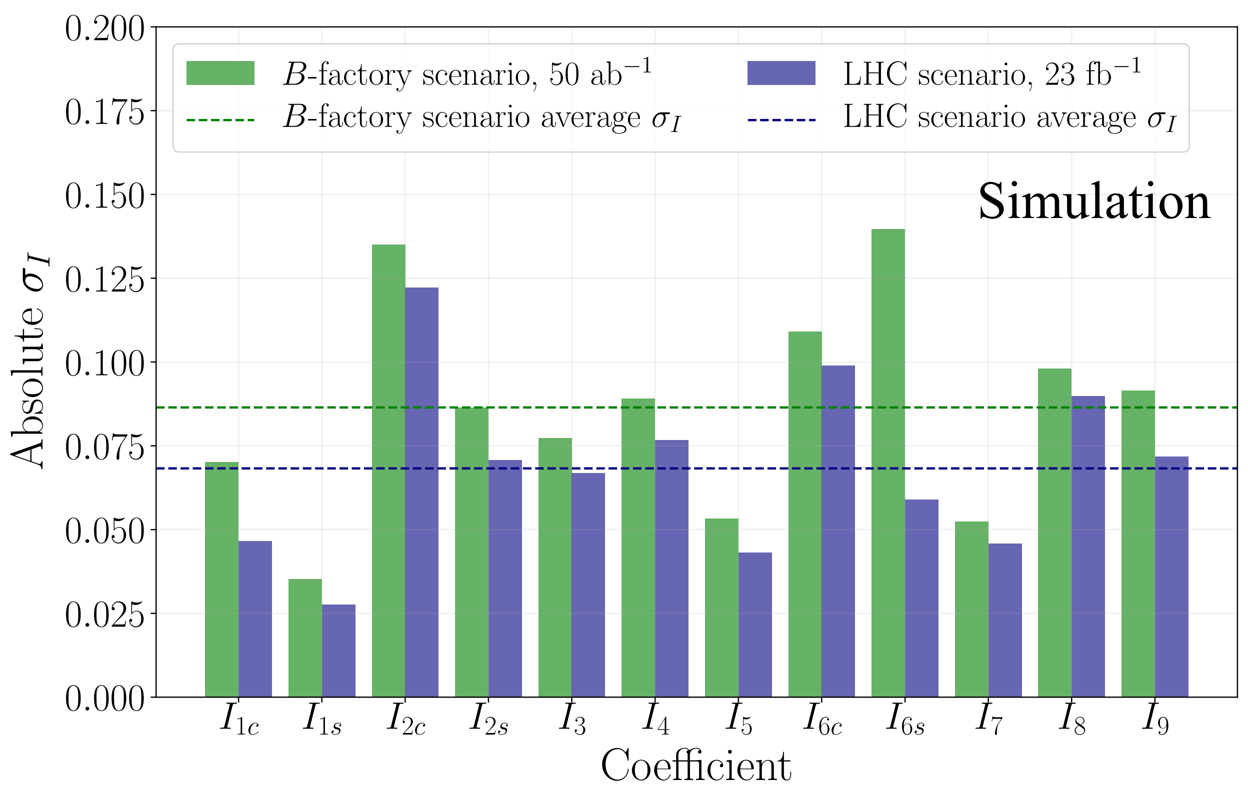












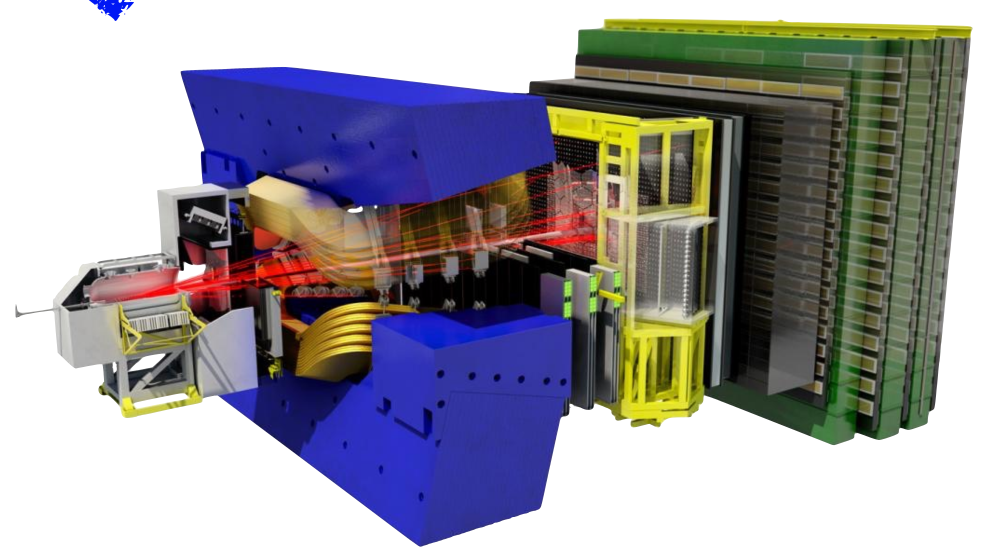
Summary

9 fb^{-1} — Goal: 50 fb^{-1} — Goal: 250 fb^{-1}

Upgrade I (LS2) — Upgrade II (LS4)

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024	2025 2026 2027	2028 2029 2030	2031	2032 2033 2034	2035	2036 2037

Belle II



- LHCb has a **unique ability** to **study $b \to c\tau\nu$ transitions**
  - $\mathscr{R}(D^{(*)})$, $\mathscr{R}(D^{**})$, $\mathscr{R}(D_s^{(*)})$, $\mathscr{R}(J/\Psi)$, $\mathscr{R}(\Lambda_c^{(*)})$ with muonic analyses
  - Kinematic distributions with hadronic analyses
- **Upgrade I** will allow us to reach 1-6% uncertainties
- **Upgrade II** would reduce some uncertainties 2× further
  - Access to important kinematic distributions, key to characterize NP
- **Challenges** ahead
  - Will need an **order of magnitude more MC** than what FastSim can do today
  - Important to **calculate** and **measure all FF** and **control other systematics**